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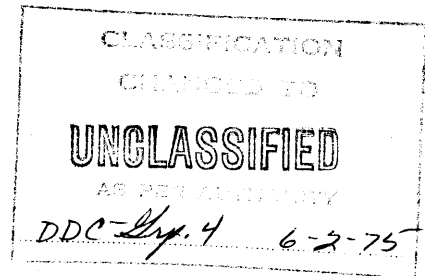
Final Report

THE MILITARY ROLE OF INFRARED DETECTION

October 6, 1952

Volume II
of two volumes

SPECIFIC PROBLEMS



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**PROJECT METCALF
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PREFACE

The various chapters in Volume II have been written by the authors noted and they were responsible for the detailed investigation. However, all of the material has been read, discussed at length, and approved by the entire Metcalf Group.

"When you wish to produce a result by means of an instrument, do not allow yourself to complicate it by introducing many subsidiary parts but follow the briefest way possible."

Leonardo Da Vinci

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Part I

THE PHYSICAL BASIS OF INFRARED DETECTION

M. Hamermesh

The purpose of this report is to give a brief but up-to-date survey of the physical quantities which determine the operation of infrared detection systems. We shall be chiefly concerned with passive detection though most of the data can be as well applied to active systems.

The various factors which must ideally be known in order to solve the detection problem are:

1. Target Signal

For each of a variety of militarily important targets, we require a knowledge of the power radiated, including its angular and spectral distribution. In some cases the target signal may exhibit a peculiar time variation which will aid in detection.

2. Background Signals

The target signal which is being sought by an IR system will be diluted with a variety of other signals from the earth, sky, water, clouds, sun, moon, and stars, depending on the tactical situation in which the target is being sought. For each of these background sources we should know the power radiated, its spectral distribution, time variation, and dependence on meteorological conditions.

3. Propagation

Both the target and background signals must pass through the atmosphere to the detector. We require data enabling us to determine the attenuation and its dependence on meteorological conditions.

4. Detection

We require a knowledge of the characteristics of detectors - their spectral sensitivity curve, minimum detectable signal, and response time.

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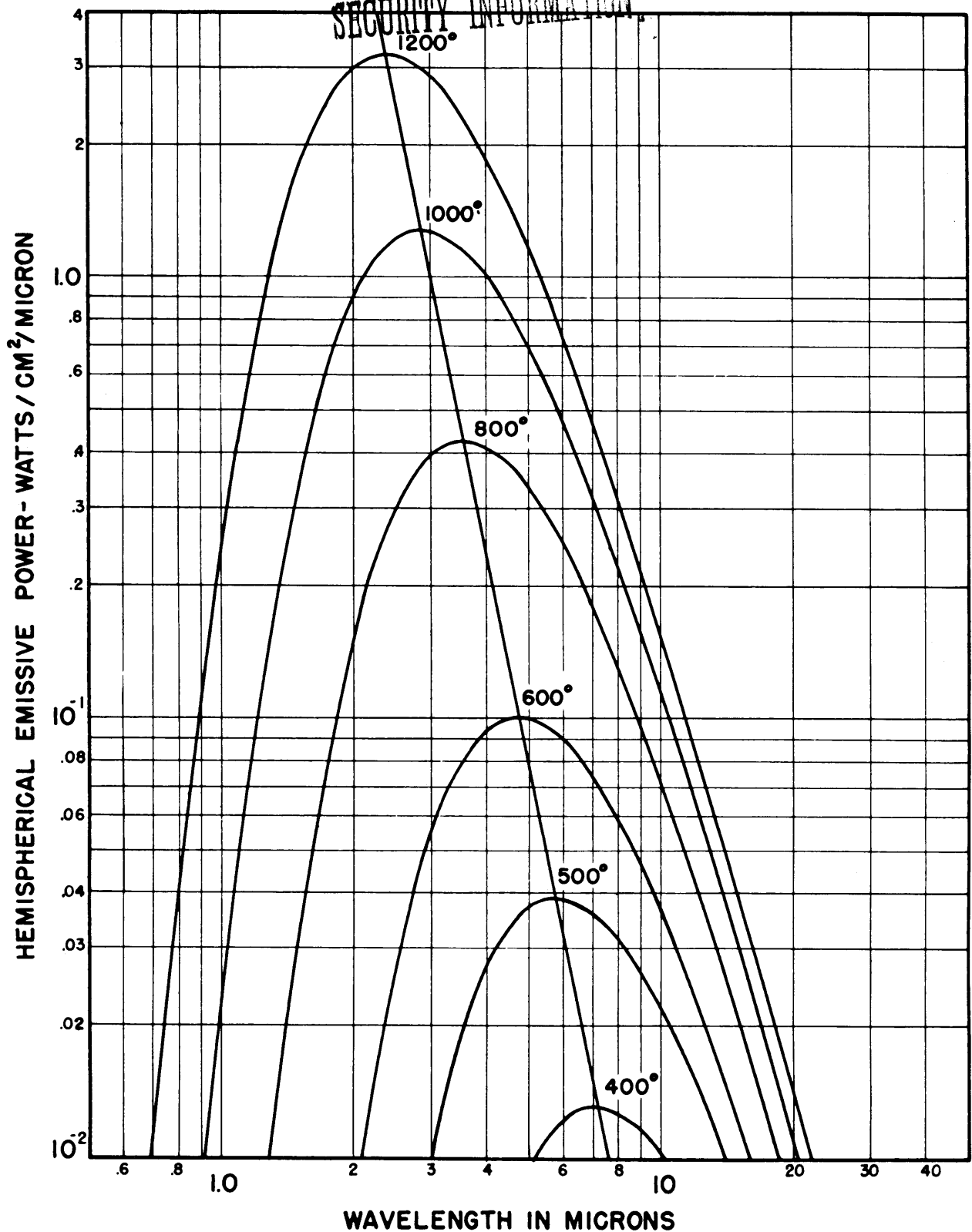


Figure 1 - Power Emitted per Unit Wavelength Band by a Black Body of Unit Area.

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5. Target-background Discrimination

The target and background have different characteristics, as functions of space, time, and spectral composition. The scanning system takes advantage of these differences and should be designed to give maximum probability of dredging up the target signal out of the mire of background signals.

We shall attempt in this and the three succeeding reports to summarize the present knowledge concerning each of these problems, and suggest research still needed in order to fill in gaps in this knowledge.

Items 1-3 are discussed in Part I of this Chapter, and detectors in Part II, while Part III gives a more detailed discussion of sky background, and Part IV deals with scanning.

Before proceeding to discuss these various problems, let us first recall some elementary facts concerning blackbody radiation and atmospheric absorption.

The continuous spectrum of radiation emitted by a hot solid is described by the Planck formula. The wavelength distribution shown in Fig. 1⁽²⁾ has a maximum at the wavelength λ , given by $\lambda T = 2.9 \times 10^3$ micron-degrees, where T is the Kelvin temperature of the radiator. The sources with which we are concerned have temperatures which lie in the range 300-1000°K. From the figure we see that for room temperature the maximum of the radiation is at 10μ , while at $T = 1000^\circ\text{K.}$, the maximum has shifted to 2.9μ . The half-power points on the short and long wavelength sides are at $\lambda T = 1.8 \times 10^3$ and $5.1 \times 10^3 \mu\text{-deg.}$ The total power contained between the half-power points is $3.4 \times 10^{-12} T^4$ watts/cm.², and constitutes 60% of the total radiation. 37% of the total power lies on the long wavelength side of this central region, while only 3% is on the short wavelength side. We see that for a body at room temperature there will be very little power at wavelengths shorter than 6μ ; for a radiator at 1000°K. , most of the power will be concentrated between 1.8 and 5μ . This concentration of power into a definite wavelength band, depending on the temperature of the radiator, already dictates the type of detectors which should be sought. For room temperature sources we must have detectors in the $6\text{-}10\mu$ region, while for high temperature sources we would prefer detectors in the $1.8\text{-}5\mu$ range. It is important to note that for a target at 1000°K. , one gains a great deal by pushing detector sensitivity from the $1.8\text{-}4\mu$ range to $1.8\text{-}5$ or $1.8\text{-}6\mu$ since there is much untapped power on the long wavelength side. On the other hand there is so little radiation beyond 10μ that studies at, say 25μ , are of doubtful value.

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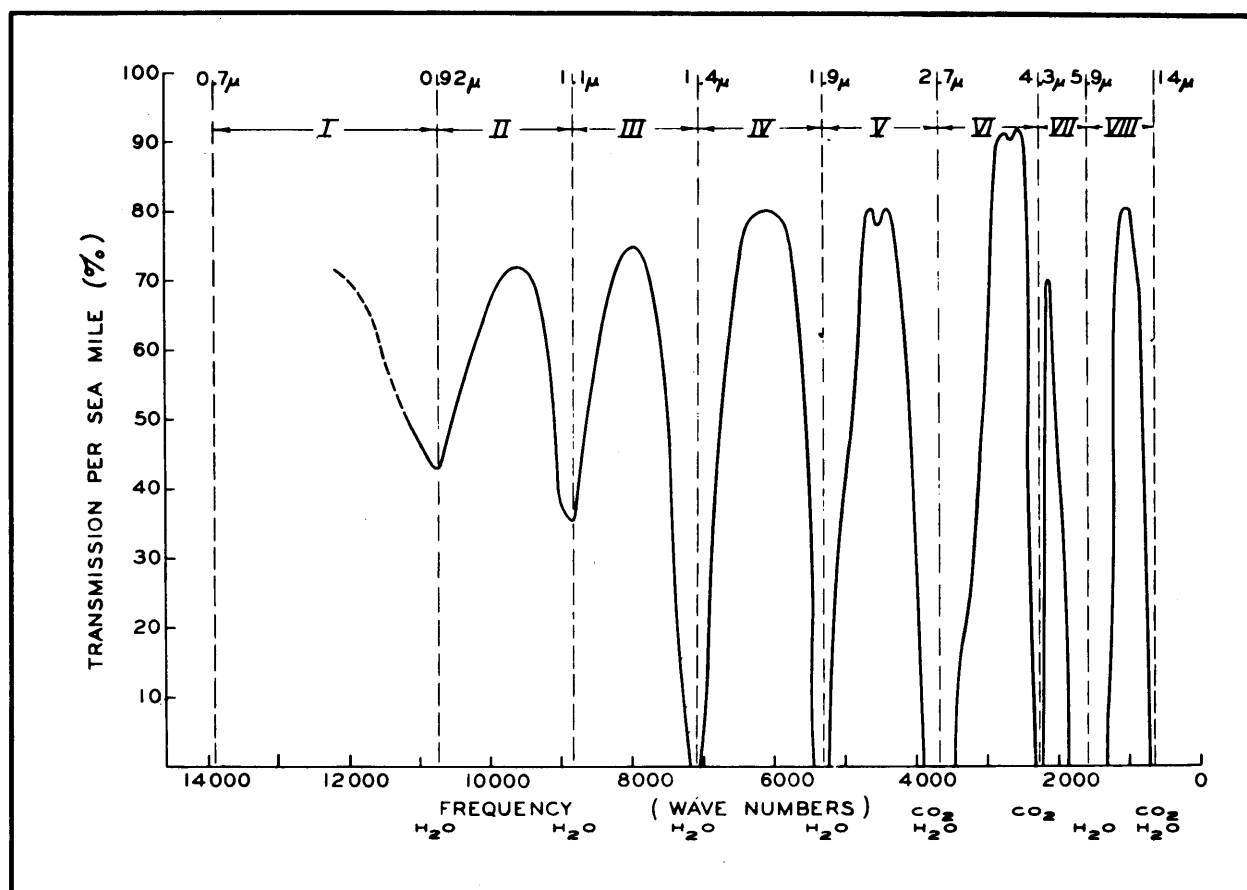
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Figure 2 - Absolute Infrared Transmission of the Atmosphere (Adapted from Bebbie, Harding, Hilsum, Price and Roberts, Proc. Roy. Soc. A206, 87 (1951))

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So far we have not mentioned another essential factor. The radiation to be detected must pass through the atmosphere. Radiation at the wavelengths which are strongly absorbed is not available for detection. The distribution of absorption bands of water vapor and CO₂ results in a series of regions of good transmission or "windows" as shown in Fig. 2⁽²⁶⁾. We note that in the infrared beyond 1.5 μ , these windows lie at 1.5-1.8, 2.0-2.5, 3.2-4.1, 4.4-5.2, and 8-14 μ . In determining the usefulness of a new type of detector, we must take these data into account. It will be useless to extend the long-wave sensitivity of a detector into a region of high absorption.

These preliminary considerations will be further amplified in the sections which follow.

1. Target Signal

The data on signal strengths from targets are scattered and incomplete. The main obstacle to obtaining this information is the cost of tests which require the use of service aircraft, ships, tanks, etc.

The potential targets are numerous:

- A. Aircraft
- B. Missiles
- C. Ships
- D. Tanks and other vehicles
- E. Buildings

A. Aircraft

Both tiedown and flight tests have been made on a variety of aircraft. The hottest parts of the aircraft are those in the neighborhood of the engine. For normal reciprocating engines the outside of the exhaust stubs is at about 400°C. and the inside at about 700°C.; while jet pipe temperatures are 500-600°C. outside and 700°C. inside.

(1) Conventional Aircraft

For propeller craft, the total power radiated in the region covered by a PbS detector, from the visible to $\lambda = 3.0\mu$, is about 1 kw. for medium planes, increasing to about 10 kw. for a large bomber. The angular distribution of the radiation appears to be determined by the positions of the exhaust stubs. Shielding the stubs could seriously reduce the radiation available for detection. Flight tests⁽⁶⁾ on a TBM (Navy torpedo bomber) using a PbS detector gave a signal of

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10^{-10} watt/sq. cm. at 5000 yards, which corresponds to a total radiated power of 2 kw. Under the test conditions, the engine developed approx. 1000 hp.

The intensity and angular distribution of radiation from a B-29 engine (1500 hp) have been measured⁽¹⁰⁾. The main sources of radiation are: inside of exhaust pipes at 700°C.; outside and ends of exhaust pipes at 450°C.; cylinders at 200°C. The radiation in the 2-2.5 μ region is the same as that of a jet engine. The polar diagram of the radiation from a single engine in the 2-2.5 μ region is shown in Fig. 3⁽¹⁰⁾. The forward radiation is low because one sees mainly the cylinders which are at relatively low temperature. In the rear hemisphere the pattern is very uniform. The radiation from the complete craft could be obtained using this diagram and a geometric layout to determine shadowing of parts of the exhaust by the aircraft.

(2) Jet Aircraft

Flight tests of the F9F^(8,9) have shown that the total radiation in the IR is 24 kw., with 2 kw. in the lead sulfide region. Ground measurements indicate that the total radiated intensity varies as the 2/3 power of the thrust. Most of the radiation in the 2-3 μ region comes from the hot inside surface of the tail pipe⁽⁴⁾. The jet gases emit mainly in narrow bands from 2-3 and 4-5 μ almost coincident with emission bands of CO₂ and H₂O. However, the emission bands of the hot gases are wider than the absorption bands of the cooler surrounding gas, and consequently there is a net amount of energy available, although it is only a few per cent of the total radiation. The CO₂ emission at 4.5 μ might be extremely important since it is a fairly strong source which is concentrated in a narrow wavelength band.

The polar diagram of a British jet engine is shown in Fig. 4⁽⁴⁾. The polar diagram of an F9F (American jet) is shown in Fig. 5 (Ref. Unpublished data from Inyokern). Note that in both cases the signal in nose aspect is very low. The results of Wright Field⁽⁷⁾ on the F80 jet seem to show a good signal in nose aspect. This difference may be due to different arrangement of the jet pipe, since the polar diagram will depend very strongly on the shielding of the hot pipe. Other ground-to-air tests on the F9F⁽⁶⁾ are open to question, since measurements at 10,000 ft. altitude and 15,000 ft. range are quoted as representative of the nose aspect, though the aspect is actually 42° off from the forward direction.

Some typical range figures are:⁽⁵⁾

For a Meteor jet in tail aspect - using the Kiel IV - at night - 20 mile range at 20,000 ft. altitude, 7 mile range at ground level, in clear weather.

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Designs for some of the newer jet aircraft incorporate what is called an "afterburner" behind the regular jet to provide greater thrust during critical periods of combat. The radiation of the afterburner in the PbS region is ~ 100 times that of present jets.

Examination of the data obtained on radiation from aircraft shows a simple though rough rule: One can calculate the radiation quite accurately from measurements of surface temperatures, assuming black-body radiation, and adding up the contributions from the various parts of the aircraft, taking into account the shadowing of one part by others. This procedure checks quite well both for the total radiation and the radiation in the PbS region.

We shall see in the later sections that this simple rule is generally valid. Earlier investigations (especially on ship targets) made use of it, but it appears to have been neglected in more recent studies. We may conclude that simple measurements of surface temperature, and radiation pyrometer measurements give all the data necessary for rough knowledge of target characteristics. All the extensive tests on range, and especially on daytime range, are really studies of background radiation. It would appear, then, that a great deal would be saved by tackling the problem of background radiation directly -- one does not need a target in order to study the background.

B. Missiles ^(2,12,13)

Here, too, the radiation is calculable if surface temperatures are known. Tieman⁽²⁾ states: "Short range ballistic missiles are expected to acquire surface temperatures ranging from 350 to 600°K., while temperatures ranging from 350 to 550°K. have been measured at different surface positions on experimental V-2 rockets.

"Surface temperatures of vertically launched ballistic missiles are not expected to reach high proportions. On the other hand, long range missiles which depend on aerodynamic forces for maintaining a flight path may possess substantial skin temperatures depending on the choice of flight mechanics and structural design."

Calculations of skin temperature of the Navajo supersonic missile have been made by Halvorsen⁽¹³⁾. At Mach 1.70, the surface temperature is ~600°K., and rises to ~900°K. at Mach 2.75.

C. Ships

Extensive measurements of IR signals from ships were made by NRL⁽¹⁴⁾ and BuShips⁽¹⁵⁾. A ship will be a thermal target having effectively two different

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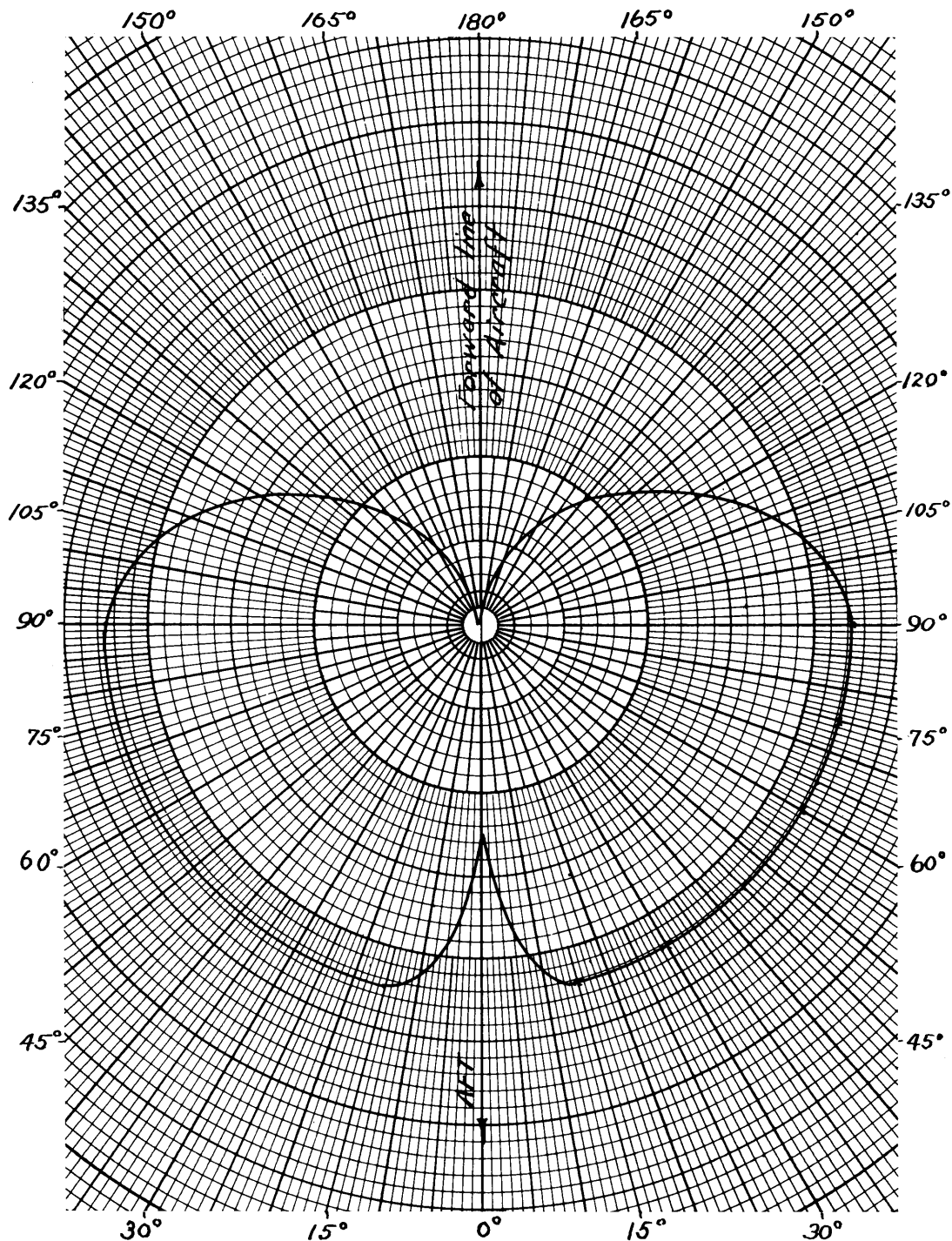


Figure 3
Polar Distribution of Radiation (2-2.5 μ Region) about a Single B-29 Engine

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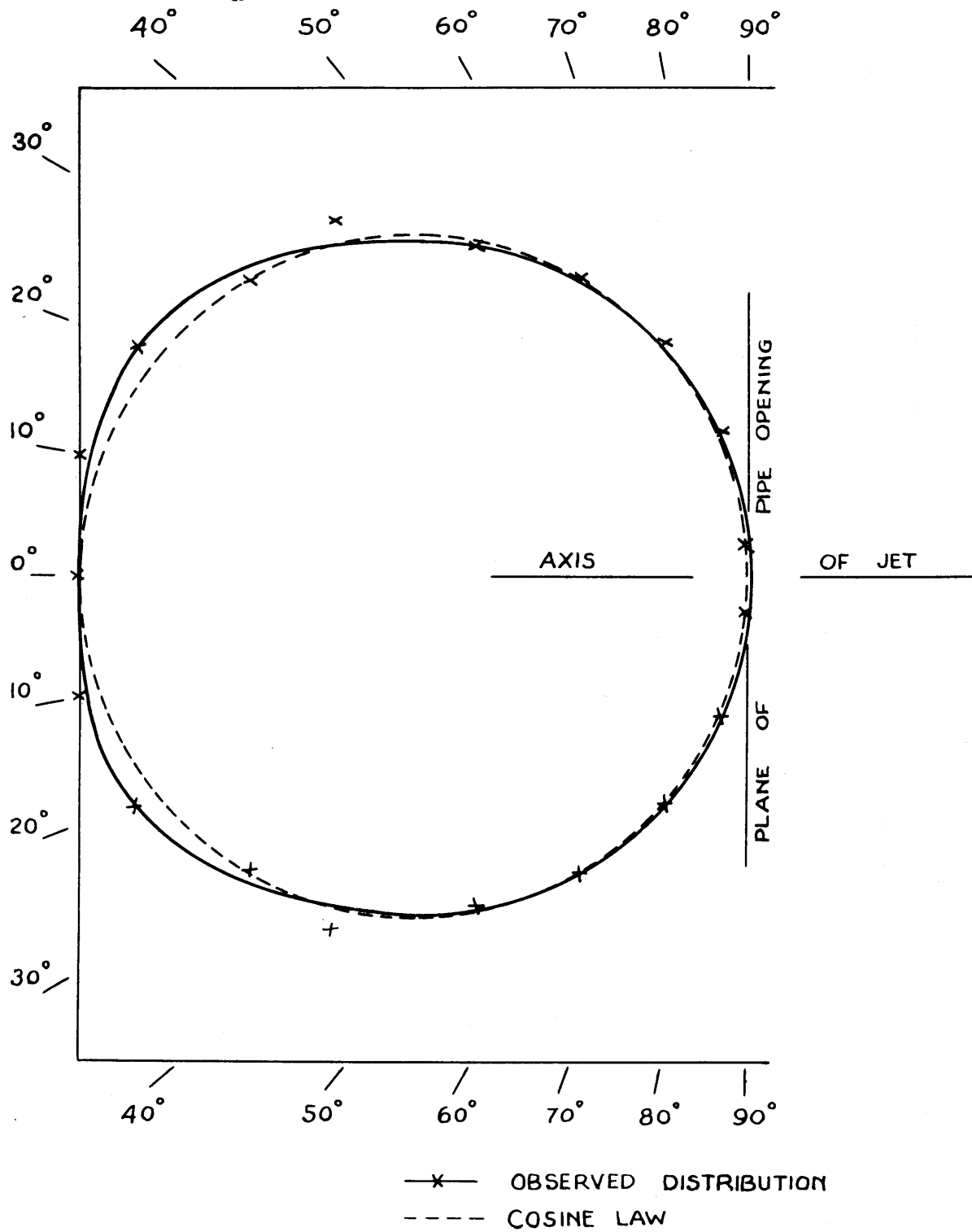
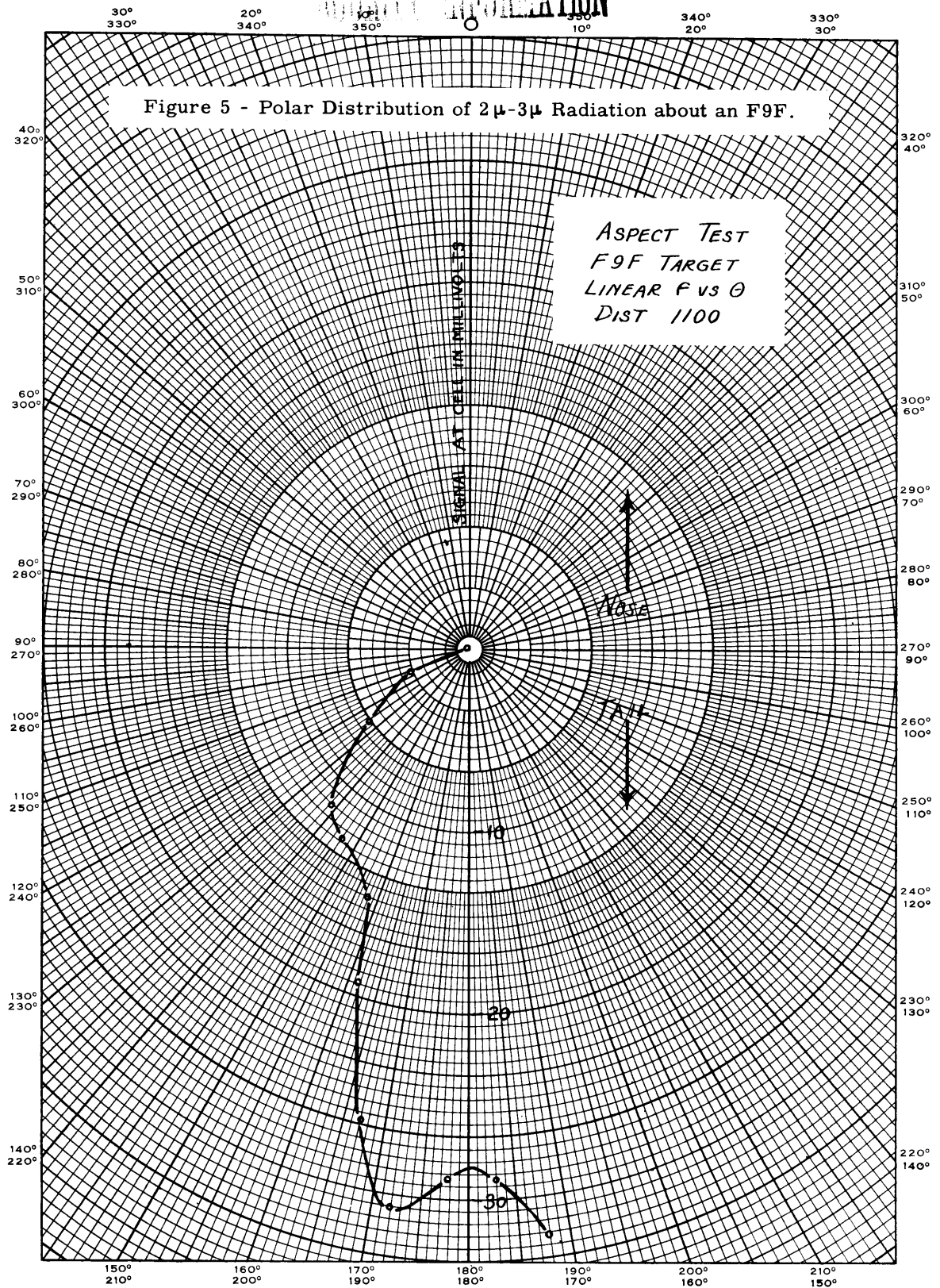


Figure 4 - Polar Distribution of $2\mu-3\mu$ Radiation about a Jet Engine.

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types of sources: the stacks at some elevated temperatures (30-90°C.), depending on speed and number of engines operating; the rest of the superstructure, which will generally be at about air temperature. Signal strengths calculated from measurements of radiation temperatures of ship surfaces give results consistent with observed IR signals. Radiation pyrometer measurements enable one to plot an infrared profile of the vessel; this profile is in fair agreement with the geometric profile, except when the stacks are imaged, giving a higher intensity. Since in many aspects the stacks will be shadowed, the effective signal can be calculated from the ship silhouette. Thus, at short ranges, when the bolometer strips of a thermal detector are completely covered by the target image, all vessels will give the same signal strength; at long range the effective signal (neglecting stack radiation) will be proportional to the projected area.

The following is a crude calculation of signal strength:

Both target and background are near air temperature T_0 , and differ in temperature by ΔT . The difference signal will be

$$I = 4 \sigma T_0^3 \Delta T A \frac{\Omega}{2 \pi}$$

where σ is the radiation constant, A is the target area, and Ω is the solid angle subtended at the receiver. The numerical result for $T_0 = 300^\circ\text{K}$. is

$$\frac{I}{A \Omega} \approx 3 \times 10^{-8} \Delta T \text{ watts/cm.}^2 \text{ deg}$$

which checks quite well with the measurements if we assume ΔT to be a few degrees.

We must emphasize that the main uncertainty here, as in most IR problems, is not the target signal strength, but rather the nature of the competing background.

D. Tanks

Early measurements by Bell Labs⁽¹⁶⁾ using the SND (bolometer detector) indicated that ranges of one mile could be obtained on moving tanks. More recent measurements⁽¹⁸⁾ using the Kiel IV (PbS cell) showed ranges of 1-3 miles on M-46 (Pershing) and M-24 (Sherman) tanks; it was noted that the tanks could be detected for some time after shutdown. The Russian T-34 tank was detected at 1/2 - 3/4 miles. The difference in range on the T-34 and American tanks was ascribed to (a) better shielding on the T-34 -- the mufflers are installed under the tank shell; (b) the liquid cooled T-34 operates at much lower temperature than the air-cooled American tanks.

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The main recent advance has been some British work.⁽¹⁷⁾ The simple procedure described in C. has been revived. Both surface temperature and radiation pyrometer measurements were made. The surface of the vehicle (a Centurion tank) was broken up into sections to each of which an effective temperature was assigned. The temperatures of parts of the exhaust lie between 200-400°C., while the top of the engine compartment is nearly 60°C. above ambient temperature. From such data the power radiated can be calculated for any aspect. Since the total radiated power is 15 kw., the application of IR to tank detection shows great promise. Detection by both PbS and bolometer have been considered. The range at night was 2,000 yards. After the engines were switched off, the signal fell to half value in 5 minutes, and to 1/10 in 12 minutes.

Shielding of the hot stubs would seriously decrease the signal in the PbS region. For ground-to-ground use by slowly moving vehicles an uncooled bolometer should still be effective. Air-borne search would require a response time which could be reached only by a photoconductive cell sensitive well beyond 3μ.

E. Buildings

Though the study of IR detection of buildings and other ground structures is only in a preliminary stage, the results so far obtained are very promising. The Servo Corporation has done thermal mapping studies⁽¹⁹⁾ of ground targets in the 10μ region, including day and night maps of Manhattan Island which are reproduced in Chapter 2. The prominence of power plants and similar buildings on such maps, particularly when made at night, makes this a valuable adjunct to radar for target location. There is a great need for continuation and extension of this work.

2. Background Signals

Studies of background signals have been few and incomplete. We shall quote the few pieces of information now available. Astronomical sources will be important for air-to-air detection and for navigation. The following table gives relevant data:⁽²⁰⁾

<u>Source</u>	<u>Total illumination at earth's surface - watts/cm.²</u>	<u>IR illumination (1.5-4.0μ) watts/cm.² at top of atmosphere</u>
Sun at zenith	.12	1.4 x 10 ⁻³
Clear sky	.015	
Twilight	5 x 10 ⁻⁶	
Full moon at zenith	2.6 x 10 ⁻⁷	
Integrated starlight*	10 ⁻⁹	10 ⁻¹⁰
First magnitude star	10 ⁻¹²	10 ⁻¹³

(* Assuming color temperature 6000°K.)

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The effective radiation temperature of clear night sky background varies with zenith angle from about -60°C. at 90° altitude to $10-15^{\circ}$ below ambient temperature at the horizon. On an overcast day, this variation will be smoothed out and the effective temperature at all altitudes will be close to ambient. For ship to ship detection, the difference between horizon and ambient temperature is the ΔT used in section 1-C.

No measurements of background signals from the earth are available; the standard calculating procedure has been to consider the unilluminated earth to be a uniform source at 300°K. In actuality, as shown in Ref. 19, the earth background shows wide nonuniformities which require study.

Some studies have been made of thermal signals from the sea. (21,22) They appear to be due to reflection of sky radiation, and can be computed from the known sky radiation and the reflectivity of water as a function of angle of incidence. At night the warm sea can act as a radiation source. In addition, the shifting of cooler water from below to the surface in the wake of a submarine and accompanying changes in emissivity can give rise to detectable signals.

3. Propagation

Signals emitted by a target will be attenuated as they pass through the atmosphere to a receiver. This attenuation will be caused by two processes: (1-3) (24) selective absorption and scattering.

A. Absorption

The main absorbing constituents of the atmosphere are water vapor and CO_2 . Their absorption bands are extremely complex but since, in all practical applications, broad spectra are used, minute details of the absorption spectrum are unimportant. Suppose that the absorption coefficient per cm. of path is $a(\lambda)$, and that the signal has a wavelength distribution of intensity $I(\lambda)$. If we knew $a(\lambda)$ completely for a given temperature and pressure (i.e., had measurements with infinite resolution), the intensity distribution after traversing a distance would be given simply by $I(\lambda) e^{-a(\lambda)d}$ (omitting the inverse square law factor $1/d^2$). Unfortunately, the resolution available in spectroscopic measurements is not sufficient to give us $a(\lambda)$. Instead, what we obtain is the transmitted intensity

$$\int_{\Delta\lambda} I(\lambda) e^{-a(\lambda)d} d\lambda$$

integrated over a spread $\Delta\lambda$ in wavelength. If $a(\lambda)$ varied slowly over the interval $\Delta\lambda$, we could write the transmitted intensity as

$$I(\lambda)\Delta\lambda e^{-\overline{a(\lambda)d}},$$

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where $\overline{a(\lambda)}$ is an average absorption coefficient for the interval $\Delta\lambda$. We know from the experimental data that this is not the case. The transmitted intensity is not simply an exponential function of distance. For short paths, the more absorbable wavelengths are filtered out; as the path increases, we are left with less and less absorbable radiation so that the apparent $\overline{a(\lambda)}$ decreases with increasing distance d .

One procedure for solving this problem is that of Elsasser.⁽²³⁾ He assumes that within any $\Delta\lambda$ there is a periodic variation of absorption coefficient. The result of his analysis is that the transmitted intensity $I(\lambda)$ is related to the initial intensity $I_0(\lambda)$ by

$$\frac{I_0(\lambda) - I(\lambda)}{I_0(\lambda)} = \operatorname{erf} \left[\frac{\beta(\lambda)}{2} (\pi w)^{\frac{1}{2}} \right]$$

where $\beta(\lambda)$ is a new "absorption coefficient."

w is a measure of the amount of absorbing material in the path of distance d (e.g., cm. of precipitable water vapor in one sq. cm. cross section), and $\operatorname{erf}(x)$ is the error function. At each wavelength λ , a value of $\beta(\lambda)$ is determined to give best fit to the experimental transmission data. Once $\beta(\lambda)$ is known, the transmission over any path length is determined from the above equation and summed for all wavelengths.

The procedure described here has been worked out in detail by Kellogg.⁽¹⁾ From the experimental data he determines $\beta_{\text{H}_2\text{O}}$ and β_{CO_2} . Kellogg then constructs tables giving the total power received by a PbS cell or a bolometer, as a function of distance, for various black-body sources and for several humidity conditions. Since there is no simple rule for epitomizing the results, the reader must be referred to Kellogg's paper for numerical values.

A procedure essentially the same as Kellogg's has been used by the Ohio State group and summarized in an NRL report by Yates.⁽²⁷⁾ The one difference is that instead of determining $\beta(\lambda)$, these authors determine one β for each absorption band. A comparison of the NRL curves and those of Kellogg shows fairly close agreement on attenuation due to absorption.

It should be realized that in preparing the tables of IR range, the experimental data which are taken over relatively short path lengths (more precisely, small amounts of precipitable water vapor) have been extrapolated to long paths by using Elsasser's formula. If they were used only for path lengths corresponding to those of the experimental measurements, the tables would be merely a convenient tool for integrating the transmission over the IR spectrum. But

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if they are extended to longer paths, we are depending on the validity of the Elsasser formula beyond the range in which it has been tested. A further difficulty with these and other methods is the uncertainty concerning pressure broadening in CO₂. The effect of the pressure broadening is not included in either of the reports mentioned.

A third procedure, proposed by Elder and Strong,⁽²⁶⁾ is the following:

The IR spectrum is divided into several regions corresponding to the windows between the water vapor and CO₂ bands. From data of various experimenters (including some measurements at fairly long paths) an empirical fit is made to the transmission as a function of precipitable water vapor. A fairly good fit is given by

$$T = -k \log w + t_0$$

where T is the transmission in a particular window, w = mm. of precipitable water vapor, and k and t_0 are constants characteristic of the window. The crude argument given by Elder and Strong in obtaining this formula is incorrect, but starting from the formulation of Elsasser and making reasonable assumptions concerning the variation $\beta(\lambda)$ within a window, one can obtain a formula similar to theirs.* The method of Elder and Strong has one excellent feature - the tremendous amount of experimental data is replaced by a small table of values of k and t_0 , from which the transmission is easily calculable. Unfortunately, their results go out only to 5.9 microns and cannot be applied to bolometer detection. For detection by a PbS cell, their table makes computations very simple. As an example, for conditions of medium water vapor content and for no haze, the transmissions in the region from 1.4 to 1.9 μ - a typical region for the lead sulfide cell--are of the order of 90%, 80% and 70% for 100 yds., 1,000 yds., and 10,000 yds. respectively. These figures are relatively insensitive to the water vapor content within the limits usually encountered in practice and illustrate the small role played by the atmospheric water vapor absorption in this region. The inverse square law fall-off is usually the important factor since it would reduce the energy from a target in the ratios 1 to 1/100 to 1/10,000 for the three ranges given above. Haze or fog if present will also limit the transmission of infrared radiation although not more severely than it does for visible light.

* The Elsasser formula applies to a region in which there is a periodic variation of absorption coefficient, with a given β . We assume that within a window β varies from a low value at the center to high values at the edges of the window. If we assume β varies exponentially, and integrate the Elsasser formula over the window, we obtain precisely the formula of Elder and Strong.

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Experimental studies of absorption require continuation along two lines - measurements over longer paths, and a study of pressure broadening. However, we feel that the present data should give fairly reliable range predictions.

Thus we conclude that if we are given the water vapor and CO₂ content of the atmosphere, the attenuation due to absorption can be predicted satisfactorily. However, in setting range requirements for IR systems, it must be clearly understood that even at a fixed altitude variations in humidity will cause considerable variation in range. A vacuum range of 20 miles with PbS detector will be reduced to 10 miles by water content 1.4×10^{-5} gm/cc. When only short ranges are required (e.g., for terminal guidance of missiles), the absorption is relatively unimportant and a range can be assigned fairly accurately; for example, a range estimate like 1.5 to 2.0 miles could be considered to cover all humidity conditions.

B. Scattering

Electromagnetic waves passing through a medium will excite oscillations of any particles in the medium. The resulting reradiation will give rise to an attenuation of the beam and a scattering or diffusion of the radiation.

The theory of scattering of electromagnetic waves by suspended particles has been developed thoroughly. The scattering cross section σ will depend on the index of refraction of the particle and the ratio of its radius r to the wavelength λ . For $r/\lambda \ll 1$, σ is proportional to $1/\lambda^4$ (Rayleigh scattering), increases to a maximum for $r/\lambda \approx 1$, then oscillates about its asymptotic value of $2\pi r^2$. For $r > 3\lambda$, σ is close enough to its asymptotic value for most purposes of calculation.

The difficulty in estimating the effect of scattering on transmission is not in the theory - if we are given the density of droplets as a function of radius, we can in principle calculate the attenuation due to scattering. But the measurements on haze and fog have shown that determination of size distribution is very difficult, and that their prediction from ordinary meteorological data is not possible. The best available data for our purposes are those of Gebbie et al.⁽²⁵⁾ Measurements were made over horizontal paths of 2,300 and 4,500 yds. with 17 mm. of precipitable water per sea mile. The transmissions at 2.18, 3.61, 10.01, and 11.48 microns were compared with photometrically measured transmissions in the visible (at 0.61 micron). Taking the transmission ("visibility") at 0.61 μ as a reference to measure the amount of haze present, the effect of the haze in attenuating the infrared radiation could be determined as a function of "visibility." Their results have been incorporated in the curves of Yates. For a given black-body source temperature, water vapor and CO₂ concentration, the percentage

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transmission between 0.7 and 12 microns is given as a function of path length, for different values of the "visibility" as determined by transmission at 0.61 micron. The use of these curves assumes a universal particle size distribution. However, from Yates' curves and from the theory presented above we note that the scattering is important mainly for short wavelengths. For sources below 500°K. the contribution of the short wavelengths is sufficiently small so that down to haze conditions corresponding to 75% transmission of 0.61 micron radiation through 2,000 yds. the total IR transmission is practically independent of haze, except at extremely long paths (greater than 30 miles). For higher source temperatures and lower "visibility," the curves should still be quite reliable.

There is still a need for work on attenuation due to scattering, especially on its correlation with meteorological information.

The effect of fog and clouds on IR transmission is very great. We can make a rough estimate as follows:

The number N of droplets per cc. is stated to be 1-100 in fog, 20-2,000 in clouds. The drop radii are extremely variable, but since they cover a broad range of wavelengths, we may choose say $r = 5$ microns and take $\sigma = 2\pi r^2$ for all wavelengths. Using these figures, the signal will be reduced at d miles by the factor $e^{-0.2Nd}$. The effect of light fog or thin cloud will not be severe, but even for $N = 50$, the intensity will be reduced to $1/e$ at 0.1 miles. We conclude that moderate fog or cloud will render IR detection inoperative. The incidence of cloud cover is quoted as 40-80%⁽³⁾ below 20,000 ft. altitude. Above 30,000 ft., little quantitative information on cloud cover is available, but its incidence is probably less than 5%. We must conclude that IR detection is a good-weather device and will be seriously affected by clouds, except for high altitude air-to-air operations.

4. Range of Infrared Systems

From the material presented in the previous sections, one can calculate the maximum range on a given target in the absence of background. Such calculations are carried out in detail in References 1-3.

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This report was written mainly for a study of high-altitude interception of missiles, but contains an excellent introduction to the physics of the IR. It discusses the radiation law, detectors, propagation, and calculation of range.

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Part II

DETECTION OF INFRARED RADIATION

G. B. B. M. Sutherland

I. INTRODUCTION

The purpose of this report is to survey in as condensed a manner as possible the various means available for the detection of infrared radiation. It is hoped that this may be of value in reviewing existing and potential military applications of infrared techniques by (a) providing the basic information on detector characteristics in a readily accessible form, (b) indicating in what directions further research might improve the performance of existing detectors, and (c) considering whether any potential methods of infrared detection have been overlooked.

From a military point of view, it is convenient to classify detectors into two general types:

- (a) detectors which give direct picture formation
- (b) detectors which merely give a signal, from which, however, a picture may be produced, if desired, by a scanning process. The former have very distinct advantages in most military applications, but existing detectors (omitting for the moment the recent improvement in the evaporagraphic method) cover such a short range (from the visible to about 1.3μ) of the infrared spectrum that they can only be used for the passive detection of high temperature sources of infrared radiation (above 300°C) or for the detection of objects illuminated with infrared searchlights at relatively short distances (less than a mile). In spite of these limitations, the items of military equipment based on picture forming detectors have hitherto undoubtedly been of greater practical value than devices based on "signal-only" detectors.

From a scientific standpoint, all infrared detectors may also be divided into two categories, viz:- photodetectors and thermodetectors; this distinction is based on the fundamentally different principles involved in the detection process in the two cases. In a photodetector, the incident quantum of infrared radiation may be considered as a sort of trigger, which causes some observable effect in the material of the detector, e.g., emission of an electron, a chemical change, or a movement of an electron from a nonconducting into a conducting energy band. In general, such detectors have a very short time of response--a great advantage

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in all military applications. In a thermodetector, the incident radiation is absorbed on a receiver element, causing a change in temperature. This change in temperature in turn produces some observable effect, either in the receiver or (more generally) in something having good thermal contact with the receiver, e.g., a small voltage in a thermoelectric junction or an increase in the pressure of a gas. Since the detection process here involves at least the partial establishment of temperature equilibrium, it is to be expected that such detectors will in general have much greater response times than photodetectors. This is indeed the case, but the thermodetectors have one great advantage in that the receiver may be "blackened" to make it sensitive to all wavelengths, whereas the photodetector can only be sensitive to those wavelengths which it happens to absorb. As matters stand at present, photodetectors have not been produced having a proved usable sensitivity at normal temperatures for wavelengths greater than 3.5μ , so that thermodetectors provide the only simple practical means for the passive detection of objects differing in temperature from their surroundings by only a few degrees. It will be recalled that the wavelength of maximum radiation from an object at normal temperatures is about 10μ .

The known methods of detection are listed below, divided into these two categories and further subdivided according to the military classification given earlier. The approximate present practical long wavelength limit of sensitivity at normal temperatures is given in brackets after each method of detection. Where no such figure is given it may be assumed that little or no military use has so far been made of this method of detection.

Photodetectors

(a) giving Direct Picture Formation

Photochemical (Photographic (1.3μ))
Photoemissive (1.0μ)
Phosphor (1.2μ)
Evaporagraphic (to at least 14μ)
Convective

(b) giving Signal only

Photoconductive (3.5μ)
Photovoltaic
Phototransistors
Thermoelectric } all
Bolometric } wave-
Pneumatic } lengths
Radiometric
Monomolecular layer
Dielectric

The present situation is, therefore, that (apart from the experimental evaporagraphic method) there are three usable methods of detection giving direct picture formation but restricted to the very edge of the infrared spectrum and four usable methods of detection giving signal only, one of which is restricted to

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wavelengths below 3.5μ . Indeed the only photoconductive cells now being manufactured in quantity (lead sulfide) have a peak sensitivity at 2.2μ and virtually no sensitivity beyond 3μ .

It should also be added that photoconductivity has recently been observed in certain materials at wavelengths in the 10μ region. However, few figures are as yet available on the performance of such detectors and these new developments will be dealt with in a later section of this report.

Before discussing the various methods of detection in detail, it is important to consider what the performance of an ideal detector of infrared radiation should be. If the detector is a thermodetector the fundamental limitation will be the noise arising from temperature fluctuations in the receiver element. This has been discussed independently by several workers^(1,2,3) and the result is that the minimum incident power detectable as a sinusoidal variation by an isolated body of area A in which the only thermal losses are by radiation, is given by

$$P_{\text{thermal}}^{\text{min.}} = 4 (A \sigma k T^5 \Delta f)^{\frac{1}{2}} \quad (1)$$

where A is the area of the body, σ is Stefan's constant, k is Boltzmann's constant, T the absolute temperature and Δf the band-width.

If we assume $A = 1 \text{ mm}^2$, $T = 300^\circ\text{K}$. and $\Delta f = 1 \text{ c.p.s.}$

$$\text{then } P_{\text{thermal}}^{\text{min.}} = 5.7 \times 10^{-12} \text{ watt/mm}^2 \quad (2)$$

This is an ultimate limit which no actual thermodetector can attain, since heat losses by conduction can be shown to increase this value. Johnson and other sources of noise in even the best thermodetectors have so far made it impossible to get below about 10 times the above limit, i.e., about $6 \times 10^{-11} \text{ watt/mm}^2$ for 1 c.p.s. band-width.⁽³⁵⁾

However, if the detector is a photodetector, then the limiting factor is no longer the temperature fluctuation in the detector element but the fluctuations in the radiation field to which it is exposed. If the detector were sensitive to all wavelengths, then the limiting sensitivity would be the same as for the thermodetector; but the fact that all photodetectors have a very limited range of wavelength sensitivity means that they are insensitive to much of the radiation fluctuation noise in the surrounding field. Consequently, the limiting figure given in (2) is well above the experimental value found for many photoconductors at the wavelength where their peak of sensitivity lies. For example, an Eastman Kodak

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lead sulfide cell (G-249-15-6) of area 2.6 mm^2 has a noise equivalent power⁽¹²⁾ of 4.7×10^{-12} watts for a 5 c.p.s. band-width at its most sensitive wavelength (2.2μ).

Thus the limited range of wavelength sensitivity of the photodetector is a most important factor in improving the ultimate limit of sensitivity of that detector within its working range. Moreover, it seems that, in practice, photodetectors do attain a performance much closer to the limit set by radiation noise than do therm detectors.

These various methods of detection will now be discussed in some detail.

II. DETECTORS GIVING DIRECT PICTURE FORMATION

The most important characteristics of the known detectors in this category are summarized in Table I. Since it is impossible to condense the information in this way without the omission of relevant factors (and so being misleading to some extent) a few explanatory notes are added below on each class, including some applications which have been made up to the present time. As far as possible, references are given documenting the figures in the table. It is particularly difficult to provide a definitive single figure for the ultimate sensitivity of a detector and to state how closely the limit set by radiation noise has been approached. Partly for this reason, and partly because it is not at all easy to deduce immediately from a figure of absolute sensitivity what the practical performance of a detector will be in a given piece of equipment, a column has been added giving performance figures of each detector in important past applications.

Photochemical

Within its wavelength range, the photographic process (which depends on the formation of silver from silver bromide) is an excellent photochemical detector of infrared radiation. So far as we are aware, all attempts to extend the range farther into the infrared have been based on the use of infrared sensitive dyes in the emulsion (neo-cyanin, kryptocyanin, etc.)

It would seem worthwhile to look into the possibility of photochemical processes, other than some modification of the time honored silver salt process, which would give infrared pictures. It is obvious that any such process would involve the use of moderately low temperatures in the final sensitizing of the plate, in its storage and use and possibly even in its "development."

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TABLE I

Detectors Giving Direct Picture Formation

	<u>Detector</u>		<u>Wavelength Range</u>		<u>Speed of Response</u>	<u>Resolution</u>	<u>Absolute Sensitivity</u>	<u>Practical Performance</u>	<u>Practical Considerations Affecting Military Use</u>	<u>References</u>
	<u>Class</u>	<u>Material</u>	<u>Total</u>	<u>Max. Sensitivity</u>						
PHOTODETECTORS	Photo-chemical	Photo-graphic Plate	Visible to 1.3 μ	0.9 μ	1/100-Severals sec. depending on brightness of object. (Note, however, remarks in last column.)	Excellent 2500 lines to the inch or even more if very slow plates are used.	Considerably below the theoretical limit. About 50-100 quanta are needed to give a developable grain.	Useful in penetrating light haze in long range photography and some forms of camouflage.	Image formed is latent requiring time and accessory equipment for development.	
	Photo-emissive	Cs-O-Ag	Visible to 1.2 μ	0.9 μ	1/10 sec. ? (determined by properties of fluorescent screen)	About 400 lines to the inch	?	1)5 mile candles* 2)object illuminated by 30 watt lamp at 75 yds. (cp. in beam 50,000) 3)Manchester bomber at 7 miles	Requires a power supply which is bulky in the models giving high intensity and definition.	4 5
	Phosphor	SrS activated with Sa and Ce	0.8 μ to 1.3 μ	1.1 μ	No figure easily available. Presumably 0.5 sec.	Inferior	? Quantum Efficiency 1/300	3 mile candles*		7
		ZnS activated with Cu and Pb.	1.1 μ to 1.7 μ	1.3 μ	Serious lag in decay time.	Inferior	?	Much inferior to SrS phosphor and never used in practice		7
THERMODETECTORS	Evaporagraph	Paraffin Film	1 to 20 μ	Probably uniform since it is a thermo detector with "black" receiver	Order of a few seconds	Recently claimed to give over 300 lines/inch	?	Have recently been improved to give fairly good thermal pictures	Would present some practical problems in its present form	8 and text
	Convective	Al Powder in amyl-alcohol		?	A few seconds	Poor	2.3 x 10 ⁻⁷ watt	Poor	Would be quite impractical in present form.	8

*Candle power of a source which can just be detected at a distance of 1 mile in a clear atmosphere.

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Photoemissive

Within its wavelength range, this is a most useful detector.^(4,5) Although the resolution in the image is greatly inferior to the photographic plate, the fact that the picture is available without development is a tremendous advantage. The most important problem here is to find whether the wavelength range can be extended. The prospects are not too bright for the following reason. The wavelength response curves of present photoemissive detectors are determined essentially by the work functions of the alkali metals Li, Na, K, Rb and Cs. This function decreases steadily as one moves from Li to Cs, and the response peak⁽⁶⁾ correspondingly moves from 0.41μ to 0.54μ . The only other element in this series is No. 87 (Francium) which need not be considered since no stable isotopes exist.

An alternative line of attack would be to see whether a very thin film of some suitable material over the present Cs-O-Ag surface would produce an appreciable decrease in the work function and hence an extension of the wavelength range of sensitivity.

Phosphors

The detectors in this class have one great advantage over photographic and photoemissive detectors. The former require time and equipment for development of the picture while the latter require rather bulky and heavy auxiliary equipment, especially the power supply. The phosphor detectors are very light and compact. However, their resolving power appears to be greatly inferior and there is a serious delay of several minutes between the time when the phosphor is activated (by ultra-violet light or a radioactive button) and it is usable. (The action of the infrared radiation is to produce a bright image on top of a decaying phosphorescence covering the whole field of view.) This restricts the application of such detectors to the observation of stationary or slowly moving sources of radiation. In practice these detectors were not used for picture formation but for the detection of signalling lamps and other point sources. The reasons for this are not made clear in the reports so far available. Presumably the contrast was much poorer than in the photoemissive detectors where the brightness of the image can be increased by raising the accelerating voltage on the photoelectrons. It will be noticed that the sensitivity to point sources of this detector appears to be greater than that of the photoemissive type (3 mile-candles against 5 mile-candles*). However, these figures may not be strictly comparable since the former is taken from a U.S. report on a U.S. detector⁽⁷⁾ whereas the latter is taken from a British report on a British photoemissive detector.⁽⁸⁾

*Candle power of source which can just be detected at a distance of 1 mile in a clear atmosphere.

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Evaporagraphic

This method, which was invented in Germany, originally for spectroscopic work, was not considered a practical proposition in World War II. Nevertheless, it should be remembered that it is possibly the only potential method which exists at present capable of giving a direct thermal picture using radiation in the 5 - 20 μ range, so important for the detection of objects only a few degrees warmer than the background. In this connection, it is of considerable interest that Baird Associates⁽⁹⁾ have recently started work on this method for the Air Force and appear to have had considerable success in modifying this method by condensing the evaporated oil on to a second film. They claim an improvement of a factor of 10 in sensitivity on the German results and can detect (1) a human hand in 5 seconds against a 25°C. background, (2) a 125°C. object in 0.2 second against a 20°C. background. The minimum contrast that can be observed is a change of 1/2°C. against a 25°C. background. They have also made thermal pictures of (1) the city of Boston at night showing considerable detail especially on hot chimneys, and (2) people and aircraft on the ground at night. The resolution is said to be 350 lines/inch, i.e., about the same as the photoemissive image tube.

It should be noted that the performance of this detector could be improved by modifying it so that the receiver element functioned at low temperatures.

Convective

Since this method⁽¹⁰⁾ involves the setting up of convective currents in a liquid through heat radiation, it appears to be quite impracticable for military application.

III. DETECTORS GIVING SIGNAL ONLY

The most important characteristics of the known detectors in this category are summarized in Table II. Before giving supplementary comments on the separate classes of detectors a few general points may be made about some of the columns in this table.

1. Wavelength Range

This is given only for the photodetectors. It may be assumed that in general the therm detectors are satisfactorily "black" in their response to all wavelengths, although it should be noted that this is by no means an easy problem and lack of "blackness" has been reported for the B.T.L. thermistor bolom-

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 TABLE II. DETECTORS GIVING SIGNAL ONLY

	Detector		Spectral Range in μ		Speed of Response in microseconds	Sensitivity: E.N.I. in watts/cm ² for 1 c		
	Class	Material	Total	Max. Sensitivity at		At specified wavelength (watts/cm ²) x 10 ⁹	Black box (watts/c	
PHOTODETECTORS	Photo-conductive	A-D type	Tl ₂ S	v to 1.2	0.95	500 to 30,000	.0019 at 0.95 μ	
			PbS	v to 3.0	(0.8 to) 2.5	12 to 1,000	.31 to .027 at 2.2 μ	63 t
			PbSe	v to 9.0	(1.8 to) 3.2	5 to 20	4.5 to 2.7 at 3.4 μ	50 t
			PbTe	v to 6.0	(2.0 to) 4.2	25	1.1 at 4.0 μ	5
	Free carrier	Si	2 to 25+	ca 25?	< 50	1 at 10 μ	17	
		Ge	3 to 14+	ca 14?	< 1000	not so far measured	< 3	
	Photo-voltaic	See text						
Photo-transistors	See text							
THERMDETECTORS	Designer (manufacturer)							
	Thermo-electric	Bi/Sb:Bi/Sn	Hornig and O'Keefe (Farrand)		36,000	7	for all λ	7
		? ?	Schwarz (Hilger and Perkin-Elmer)		150,000	6.5	for all λ	6.5
		? ?	N.R.L. (Eppley Labs)		80,000	?		?
	Bolo-metric	NiO, MnO, CoO	Becker et al (BTL) (unbacked)		25,000	18	for all λ	18
		MnO, NiO, CoO	{Becker et al (glass backed)	5,900	120	for all λ	120	
		(Servo Corp.) (quartz backed)		2,700	80	for all λ	80	
		Pt. (Au)	N.R.L. (Baird Associates)		1,400	750	for all λ	750
		NbN	Andrews (never made commercially)		1,400	43	for all λ	43
		PbP bronze	Daunt (in research stage)		3,000 (est.)	.003 (est.) for all λ		.00
	Pneumatic	Golay (Eppley Labs.)		25,000 (approx.)	26	for all λ	26	
				3,000 (approx.)	~ 600	for all λ	~ 600	
	Radiometric	See text						
	Monomolecular Film	See text						
	Dielectric	See text						

TABLE II

cps band width ly at 500°K. m ²) x 10 ⁹)	Chopping	Area	Practical Performance	Practical Considerations Affecting	Reference
	Frequency (cps)	in cm ²		Military Use	
o 3.2 o 31 .4	90	3.9	3 to 6 miles on voice communication	Non-linear at high signal levels. Sensitive to certain background radiation.	21
	90	.11 to .36	Detection of tanks 1-3 miles Detection of aircraft 20 miles	No special drawbacks.	12
	90	.12 to .045	Not used so far	Very difficult to produce reliably good cells, therefore, hard to make a quantity.	12
	90	.025	Not used so far	Must be operated at liquid air temperature.	12
	1000	.36	Not used so far	Must be operated at liquid helium temperature.	26
	25	.20	Not used so far	Must be operated at liquid helium temperature.	28,29
03 (est.)	5	.01	Only used in spectroscopy	No special drawbacks	35
	5 ?	.004	Only used in spectroscopy	" " "	8
	?	.23	Used in Wake Detector	" " "	
	15	.004	Thermal scanning	No special drawbacks	31,32
		.005	Thermal scanning	" " "	33
		.005	1 mile range on tanks	" " "	33
	120	.0024	?	" " "	36
	27.6	.008	Thermal scanning	Requires liquid H ₂ and careful thermostating.	11
	100 ?	.01	Not used	Requires liquid helium	34
	14.6	.071	Not used	Must not be overloaded. Delicate and	11
	140	.01		subject to microphonics.	

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eters at certain wavelengths and for the Schwarz thermocouple at wavelengths beyond 8μ .

In the case of photodetectors, it is impossible to describe the spectral sensitivity adequately by means of figures in a table since it is so nonuniform. Even more serious is the fact that the spectral sensitivity depends on the method of manufacture and indeed on the individual laboratory (cf. the variation in such curves for PbS in the Bureau of Standards report).⁽¹²⁾ Until the production of such detectors becomes a science, rather than an art, this situation is likely to continue. The low wavelength values for the point of maximum sensitivity have been put in brackets, since these are of little practical interest. In the column labelled "Total", v. is short for "Visible."

2. Speed of Response

As far as possible, the figure given represents the time to achieve $(1 - \frac{1}{e})^{\text{th}}$ of full response. Here again it is not possible to give a single figure which describes this characteristic. What is required for each detector is a graph showing signal/noise v. frequency of chopping and how this can be varied as a function of the construction parameters.

3. Absolute Sensitivity

This is really tied up with the two preceding columns on speed of response and spectral sensitivity, as no single figure is adequate to describe the absolute sensitivity of a detector. What is required is a series of graphs (such as those being produced by Bureau of Standards Laboratory⁽¹²⁾ at Corona) giving equivalent noise input (E.N.I.) as a function of wavelength for various chopping frequencies since for the PbS, PbSe and PbTe cells, noise is inversely proportional to chopping frequency. (The B. of S. curves are at present only for one chopping frequency.) This information does not exist at present, except in very fragmentary form, scattered throughout various reports, and the Bureau of Standards program should be extended to cover all potentially useful detectors and so provide this information. From such curves, it is possible to derive the sensitivity of any detector to a black body source at a given temperature by computation. However this is a clumsy process and for many purposes a single figure (sufficient for many practical applications) can be obtained by direct tests against black bodies at various temperatures. Such tests have indeed become a "standard" way of giving a figure for many detectors. Thus, the present "standard" U.S. test (Corona) for a photoconductive cell⁽¹³⁾ gives the noise equivalent power (or E.N.I.) for a black body at 500°K . using a 90 c.p.s. chopper and a band width of 5 c.p.s. in the amplifier, the flux density at the detector being 12.5×10^{-6} watts/cm². The "standard" British test for a photoconductive cell at present is the signal/noise ratio from a black body at 200°C . using an 800 c.p.s. chopper

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and a band-width in the amplifier of 50 c.p.s., the aperture of the black body oven being 0.28 cm^2 and the detector being 20 cm. from it. Provided the limitations of such figures are clear to the user, they can be of considerable value. We have accordingly tried to give two figures for the absolute sensitivity of each photodetector.

The first figure refers to the sensitivity at the maximum (or at an important) wavelength for the photoconductive detectors; the second figure gives the response to a black body on the U.S. "standard" test followed by the chopping frequency and the area. These figures have been recalculated to a band-width of 1 c.p.s. on the assumption that the E.N.I. is proportional to the square root of the band-width. In all cases the E.N.I. has also been recalculated (where necessary) so that it is expressed as watts/cm². This was done by simple proportion but the area of the element is given in the next column so that the absolute figure can easily be computed if desired. Objections may be made to this method of reducing sets of figures from various sources to a common basis. For instance, it has been customary for many workers to use the square root of the area rather than the area itself. Yet examination of experimental data indicates that neither is correct, but that in some cases (area)^{0.8} might yield a truer representation. Similarly, in some cases it might be more correct to use the band-width rather than the square root of the band-width. In this report, the object was not to get definitive values but a comparable set of figures from which broad conclusions could safely be drawn.

4. Practical Performance

Here it is extremely difficult to decide the most suitable example and no claim is made that the best examples have been chosen as in the available time it has not been possible to survey the extensive number of reports from which examples might have been chosen. We now pass to a consideration of each class of detectors.

5. Photoconductors

These are subdivided into two types, according to the mechanism of the photo-effect. The first type is called "A-D" (Acceptor-Donor, for want of a better name at present, as the exact mechanism is still the subject of controversy), and the second type will be referred to as "free carrier." The spectral responses are very different as illustrated in Fig. 1. The A-D type each have a very sharp cutoff in the relatively near infrared which corresponds closely to the edge of the absorption spectrum found in a single crystal of the material. The free carrier type (apart from a photoconductive effect of a different nature with a sharp cutoff between 1 and 2μ , which we shall ignore) have a response which starts being

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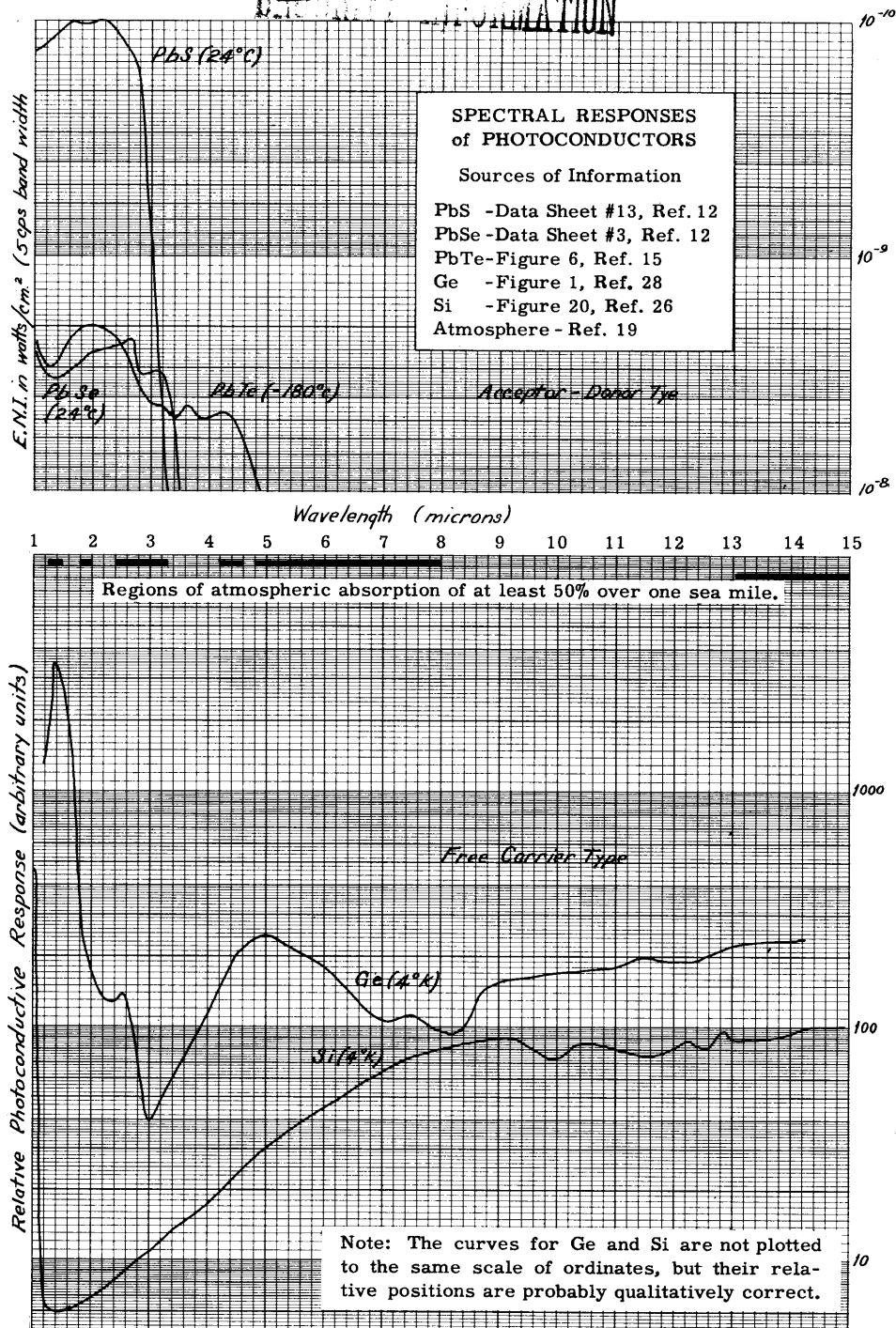


Figure 1

effective about 3μ and gradually increases to a maximum yet to be determined, but probably beyond 20μ . It should be noted that in the free carrier photoconductors absorption bands are undesirable, causing minima in the response curve as they "steal" quanta from potential free carriers.

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The A-D type have a great practical advantage in that the first three (Ti_2S , PbS , and PbSe) exhibit their properties at room temperature (although PbSe does not go much beyond 3.5μ except at temperatures below that of liquid O_2) or liquid air temperatures (for PbTe and PbSe to 8μ) whereas Si and Ge , as presently developed, require operation at liquid helium temperature. The E.N.I. for the A-D type is at present comparable to that for the free carrier type for a black body at 500°K . The time constant of the free carrier type, although as yet only measured to be below 10^{-4} second, is believed (by Rollin)⁽¹⁴⁾ to be about 10^{-9} sec.

One other general remark may be made about the PbS , PbSe , and PbTe photoconductors. It is clear that as the spectral response moves out into the infrared such photoconductors will start to be activated by the short wavelength tail of room temperature radiation (whose maximum is about 10μ). In order to get the maximum signal/noise ratio, the photoconductor should, therefore, be shielded from the surrounding radiation field. This effect was first observed for lead telluride by Simpson⁽¹⁶⁾ (and has since been found by others^(17,18) for PbS) who surrounded the cell with a cold background (-190°C .) and found the signal/noise was considerably increased. This effect should be further investigated, as should the possibility of improving the performance of all photoconductive detectors (beyond 2μ) by enclosing them within cold containers and admitting the signal radiation through a cold filter and chopper with an appropriate band pass. In this connection it may be important that the transmission of the atmosphere⁽¹⁹⁾ is very high around 10μ so that a photoconductor used only in that region is "looking" into an ideal cold radiation background viz. that of outer space. (Fig. 1)

A related question is how sensitivity for particular wavelength ranges depends on the shape of the spectral response curve. Since in the case of A-D photoconductive detectors the majority of the background radiation is normally of greater wavelength than the wavelength for maximum responsivity, it is disadvantageous for an unshielded detector to have appreciable photosensitivity at wavelengths greater than that of the signal. Sensitivity in the long wavelength tail of the spectral response curve adds appreciably to the radiation noise. Calculations by Moss⁽²⁰⁾ show that the limiting sensitivity for a lead sulfide cell at 2.3μ deteriorated from 5.2×10^{-14} watt at 273°K . to 17×10^{-14} watt at 90°K . because of the change in spectral response on cooling (see below), the responsivity at long wavelengths being preferentially increased at low temperatures. On the other hand, the limiting sensitivity at 3.5μ for the same detector improved from 2×10^{-11} watt at 273°K . to 1.5×10^{-13} watt at 90°K .

We next give some comments on the individual photodetectors.

(a) Thallium Sulfide. This detector appears to have been developed to its limit by 1945⁽²¹⁾ and no further comment is necessary.

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(b) Lead Sulfide. An immense amount of effort has been put into investigations on PbS cells and only a few of the salient points can be picked out for comment here.

PbS cells may be manufactured by a chemical process or by an evaporation process.

The best chemical cells⁽¹²⁾ are made (in quantity) by Eastman Kodak having (at room temperature) time constants between 4.0×10^{-4} sec. and 10^{-3} sec., a maximum sensitivity near $2.2\mu^*$ (with a sharp fall beyond 2.8μ) varying from 3.2×10^{-10} watts/cm² to 2.7×10^{-11} watts/cm², and a U.S. standard 500°K. black body test figure varying from 3.5×10^{-8} watt/cm² to 3.3×10^{-9} watt/cm², all measured at 90 c.p.s. These cells appear to be the most uniform of all PbS cells as regards "spot" sensitivity within the area of the PbS layer.

Evaporated layer cells are made by Cashman (Northwestern), Continental Electric Co., Chicago (known as "Cetron" cells), Photoswitch (Cambridge, Mass.), Admiralty Research Laboratory (Baldock, Herts, England), T.R.E. (Malvern, Wores, England), and the Paris Observatory (France). Until representative samples have been tested at Corona it is not possible to say which of these are best. The spectral response curves of these cells are very variable (depending on the "oxygen treatment" given to the layer), the point of maximum sensitivity varying from 0.8μ to about 2.5μ . The time constant varies from 1.2×10^{-5} sec. to 2×10^{-4} sec., i.e., appreciably faster than the chemical cells. The better cells have an E.N.I. of about 1×10^{-10} watt/cm² for 90 cycle chopping around 2.2μ and a U.S. standard 500°K. black body test figure around 1.5×10^{-8} watt/cm². It will be observed that these sensitivities are appreciably worse than corresponding figures for the chemical cells so that the increased speed of response is only achieved by sacrificing sensitivity.**

It should be mentioned that the two limiting cases chosen for use in the table (in columns 4, 5, 6, 7 and 8) are (1) one of the fastest evaporated cells (Cashman N.U. 5144), and (2) one of the most sensitive chemical cells (Eastman Kodak G-242-9-1).

* This wavelength was chosen because it is at the peak of the 2.0 to 2.5μ atmospheric window.

**However, we have subsequently been informed that twelve Eastman Kodak chemical cells recently tested at T.R.E. yielded signal-to-noise ratios of approximately the same magnitude as comparable Mullard evaporated cells under British standard test conditions, although the time constants of the Eastman Kodak cells were greater by a factor of ten. (Mullard is making the T.R.E. cell on a quantity basis.)

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The effect of lowering the operating temperature on both types of cell is important.^(12,15,22) Cooling the layer to dry ice temperature ($-72^{\circ}\text{C}.$) improves the E.N.I. by a factor varying between 6 and 100 but increases the time constant by a factor varying between 1 and 60. The time constant is much less affected by lowering of temperature for evaporated cells than for chemical cells. These effects are enhanced by lowering the temperature to that of liquid air and liquid hydrogen. At these lower temperatures another important effect appears⁽²³⁾ in that the spectral response is extended by about 0.5μ , putting the edge of the steep fall-off out to about 3.2μ . It should be remarked that all the figures in Table II on PbS refer to room temperature operation.

(c) Lead Selenide. The figures quoted here are taken from the Bureau of Standards Report⁽¹²⁾ which lists characteristics on 3 Cashman cells and 2 Admiralty cells for room temperature operation. The spectral response of all these cells falls off very rapidly around 3.5μ . The long wavelength limit of 9μ quoted in column 3 refers to a very new development⁽²⁴⁾ at T.R.E. (Malvern). There it has been found that thick layers ($4-5\mu$ as opposed to the usual few tenths μ for this type of photoconductive layer) exhibit a considerable sensitivity, out to nearly 8μ at liquid air temperatures and to nearly 9μ at liquid hydrogen temperatures.⁽¹⁴⁾ At present the peak sensitivity is only 1% of that of a good PbS cell at its peak. This is a most surprising and important effect since it upsets what has for some time been regarded as a natural progression in the long wave limit of sensitivity in moving along the series sulfide, selenide to telluride.

The specified wavelength was chosen to be 3.4μ because the atmospheric window between 3 and 4μ has got up to 50% transmission here over 1 sea mile. The peak of this window is about 3.8μ where the corresponding figure⁽¹²⁾ for the most sensitive PbSe cell for long wavelengths, (A.R.L. W-9) is 1.2×10^{-8} watt/cm² for 90 c.p.s. chopping frequency. As for lead sulfide, the two extremes chosen are the fastest and the most sensitive U.S. cells (Cashman N.U. 3835 and N.U. 3846, respectively).

(d) Lead Telluride. The data under speed of response and sensitivity are for the fastest and most sensitive U.S. cell (Syracuse cell, S-43) recorded.⁽¹²⁾ It is known,⁽²⁵⁾ however, that slower but more sensitive British cells have been made although detailed figures are not available. It should be noted that the lead telluride cell is the one which really takes advantage of the whole of the $3-4\mu$ atmospheric window and it would be an immense advance if telluride cells could be made which were sensitive at dry ice or better still at room temperatures. Some progress has been made in this direction by Cashman at Northwestern who in a recent report⁽¹⁵⁾ gives the following results on a cell (N.U. 5040) operated at $23^{\circ}\text{C}:-$

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E.N.I. of about 10^{-8} watt/cm² at 90 c.p.s. from 0.6 to 3.4 μ , from which point the sensitivity drops sharply to 10^{-6} watt/cm² at 4.4 μ .

The 500°K. black body figure for the cell is not quoted for room temperature operation but is given as 3×10^{-7} watt/cm² at 90 c.p.s. when operated at dry ice temperatures (-72°C.). Roughly speaking one may say that at present a room temperature lead telluride cell has about the same spectral response curve as a room temperature lead selenide but is down in sensitivity by a factor of about 10. It should be added, however, that the time constant for this same telluride cell is given as 5×10^{-6} sec. at -72°C., and its response was presumably too fast to measure at room temperature.

(e) Silicon. The figures quoted are all taken from the N.R.L. work by Burstein, Oberly and Davison.⁽²⁶⁾ Essentially the same figures are being found by Rollin⁽²⁷⁾ at Oxford. The performance of this detector at higher temperatures requires further investigation. It has been stated by Rollin⁽¹⁴⁾ that he finds the sensitivity is only worse by a factor of about 2 at liquid hydrogen temperatures but thereafter it worsens very rapidly.

There appears to be an anomaly in the N.R.L. figure of 1×10^{-9} watt/cm² for the sensitivity at 10 μ since if this were true it should lead to a much lower figure than 1.7×10^{-8} watt/cm² for the sensitivity to a black body at 500°K.

(f) Germanium. The figures quoted here are all from R.C.A. work.^(28,29) It may be added that on the black body test there was evidence of saturation since decreasing the black body temperature from 500°K. to 410°K. produced very little change in signal. It should also be mentioned that the R.C.A. workers feel that this is an impurity effect and that the Ge is known to contain traces of As.

There is a very recent verbal report (Eldredge to us in London) that the N.R.L. group have found very promising results with Ge "loaded" with Zn. This was stated to be better than Si by a factor of 20 and good to beyond 32 μ at liquid helium temperature. The response was entirely gone at liquid H₂ temperature.

6. Photovoltaic Cells

Although photovoltaic effects⁽⁸⁾ have been observed for PbS photoconductive layers over the same spectral range and these effects are of great value in the study of the mechanism of this type of photoconductivity, the sensitivity figures in general have been very discouraging and the chances of achieving a practicable detector based on this phenomenon appear to be very small.

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7. Phototransistor Cells

Many photoconductors⁽³⁰⁾ exhibit phototransistor effects. As in the case of the photovoltaic effect, the sensitivity is generally much less than that associated with the photoconductive effect, but possibly this is worth further investigation.

8. Thermoelectric

With regard to the figures given for the Schwarz thermocouple, it should be added that newer ones have faster times of response but exact figures on their equivalent noise input are not available. In view of the extensive and intensive research which has been made on thermocouple design, especially during World War II, it seems unlikely that much further progress can be expected in this field. In general, thermocouples are more sensitive but slower in response than bolometers.

9. Bolometric

The first three bolometers are generally referred to as thermistor bolometers (having negative temperature-resistance coefficients). These may be made with (1) no backing to the flake, (2) with glass backing, or (3) with quartz backing. The Bell Telephone Laboratories^(31,32) pioneered the development of thermistor bolometers, but recently improvements have been made in the backed bolometers by Servo Corporation.⁽³³⁾ In general, for receivers of comparable small area, unbacked bolometers are more sensitive but also slower in response than backed bolometers (in which quartz is superior to glass). However, larger area quartz backed bolometers can be made with sensitivity comparable (14×10^{-9} watt/cm²) to the unbacked bolometer and with very good time constants (4×10^{-3} sec.).

The last two bolometers are in a class by themselves, since these represent attempts to exploit the great gain in sensitivity which should be theoretically possible by operating a bolometer at very low temperatures. It will be observed that although the Andrews bolometer appears to have achieved⁽³⁷⁾ figures for sensitivity and time constant equivalent to having the combined best features of an air backed and quartz backed thermistor bolometer, it still falls far short of what may be hoped for in this field, as illustrated by the estimated performance of Daunt's bolometer.

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The NbN bolometer has been in rather a dormant state in the U.S. for the past few years but the T.R.E. group in England have recently become active in this field and consider that one of the main reasons why the Andrews version of this bolometer failed to give all that might be expected of it lay in the failure to cool the transformer nearest to the detector element to the same temperature as the element. It may well be that this modification (which they are now making) will lead to a substantial improvement in the E.N.I. figures. It should be emphasized, however, that the NbN bolometer requires very accurate thermostating since it operates on the very steep edge of the superconducting curve. In this respect the Daunt bolometer appears to be a better proposition, since the combinations of metals used in this detector give rise to a much less abrupt transition from conductivity to super-conductivity and so accurate thermostating is not a serious problem. The important point to realize here is that the greatest potential improvement being sought for in the low temperature bolometers lies not so much in increase of signal as in reduction of noise.

Finally it should be added that the estimated figures quoted for the Daunt bolometer will not be achieved without adequate shielding from room temperature background radiation (cf. remarks on shielding of photoconductive detectors which operate at low temperatures).

10. Pneumatic

No particular comments seem to be called for here in view of the serious practical disadvantages, mentioned in the last column of Table II, this detector would encounter in most military applications, and the fact that it seems to be not significantly better in performance than the best thermocouples and bolometers.

11. Radiometric, Monomolecular Film and Dielectric

None of these methods appear to show much promise. The radiometric has too slow a time of response and is impractical from the mechanical standpoint for use in military equipment. The monomolecular film⁽³⁸⁾ has very good signal but extremely bad noise characteristics and also appears to be very impractical. The dielectric bolometer has proved very disappointing in performance.⁽⁸⁾

All these methods suffer from the drawbacks common to thermometers as compared to photodetectors.

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IV. INFRARED PICTURE DEVICES USING A SCANNING PROCESS

The military value of a device which will give a picture of any area containing objects of military interest using infrared instead of visible radiation needs no emphasis. A great deal of effort has been expended on research in this field, but the problem has only been partially solved. In the second section of this report, the situation with respect to detectors which yield a direct picture has already been reviewed. The purpose of this section is to review briefly the present position on picture forming devices which use "signal-only" detectors in conjunction with some scanning process.

Before the very recent revival and improvement of the evaporagraph, none of the direct picture detectors had any sensitivity to radiation of wavelength appreciably longer than 1μ . During the last war, several attempts were made to produce pictures from radiation in the 8 to 12μ atmospheric window by using a thermistor bolometer as the detector element coupled with a suitable optical and scanning arrangement. These have been very fully described in a survey report⁽³⁹⁾ and there is no need to give a long discussion of their performance here, especially as it seems that there is not room for any great improvement in the best of these devices until a bolometer is produced which is superior to the thermistor type. By way of illustrating what was achieved by these methods we quote some figures⁽³⁹⁾ for the Stabilized Ship Detector (SSD). This had a field of view 40 minutes high and 8 minutes wide which could be scanned over any angle up to 360° , the optical unit being oscillated at 6, 12 or 18 degrees per second. Reliable tracks of ships were found at distances varying between 5 and 12 miles depending on the size and aspect of the vessel and on the atmospheric conditions. This is of course only a very crude picture device. A better example is the thermal map of Manhattan, which was made with the Servo Corp. equipment, again based on a thermistor bolometer. It is reproduced in Chapter 2.

There are two main objections to equipment of this type. The time of response of the bolometer limits the rate of scanning to such an extent that the picture is produced too slowly for many applications, and the engineering problems involved in the mechanical type of scan are not inconsiderable. The use of a photoconductive detector element overcomes both these objections, since the response time is very much faster and the scanning is done by an electron beam. There are additional advantages in using a photoconductive detector arising from its greater ultimate sensitivity and from the fact that it opens up possibilities of storage and integration effects. Most of the postwar research effort on picture forming devices has therefore been rightly concentrated on exploring the potentialities of various photoconductive detectors. It should be mentioned that even during the war an exploratory device (IIR) based on the lead sulfide cell⁽³⁹⁾ gave detection ranges for personnel against foliage which were comparable with those

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achieved by a bolometer device (PND), while for ships the range was as much as half that given by the SSD equipment referred to above, although the lead sulfide cell was said to be receiving only about 0.1% of the total energy radiated by the ship. It should be added that the scanning was done mechanically in the IIR device.

A group at the R.C.A. (Princeton) Laboratories have made considerable progress in the development of picture forming devices which employ photoconductive surfaces as the detecting element. The first of these (Army ERDL Project 8-23-08-003) is similar to the electron mirror device partially developed in Germany during the war. It was hoped that lead sulfide layers having a spectral sensitivity out to 3μ could be used, but in order to get the correct physical characteristics it has been found essential to change to a surface which is predominantly lead oxide with some lead sulfide incorporated. As a result, the spectral range hardly exceeds 2μ . The performance of this equipment in the field is not yet known. Laboratory tests show that it is capable of "seeing" a black body at a temperature of 200°C . The possibility of extending the spectral range by using lead oxide/lead selenide layers is being investigated. The second project (Joint Air Force and O.N.R., Contract NR 015208) is for an equipment which will respond to wavelengths out to at least 12μ . This has not got beyond the stage of searching for a suitable photoconductor, and has been referred to already in section III of this report. Here the discovery of the photoconductive properties of germanium out to at least 14μ is a distinct advance, but it should be recalled that this only operates at liquid helium temperatures. Furthermore, it is not yet known whether layers of Ge can be made having the other physical characteristics necessary for an image device. It is perhaps not irrelevant to point out here that although the photoconductivity of lead sulfide has been known for about 10 years, there is still no image tube which covers the same spectral range as the "signal-only" detecting devices based on lead sulfide.

A group at the Capehart-Farnsworth Laboratories under contract from BuShips (NObsr-52486) have been working for some time on a far infrared image orthicon, using a very thin blackened glass film as the detector element, i.e., a thermodetector. From the reports available to us, the results to date are rather discouraging. The temperature of a source which can just be detected varies between 150°C . and 240°C . and the corresponding radiation density falling on the glass film varies between 8×10^{-4} and 2×10^{-3} watts/cm². Considering that the R.C.A. lead-oxide-sulfide photoconductor can also detect objects at a temperature of less than 200°C ., (although it is sensitive to less than 0.1% of the radiation from them) the prospects of success with the Capehart-Farnsworth method appear to be very small. Even in the present equipment, very serious difficulties are being encountered in getting glass films of sufficient uniformity.

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A more promising method of utilizing a thermodetector would seem to be that being investigated by the English Electric Valve Co., at Chelmsford, England. The detector element here is a very thin film (about 0.2μ) of silicon monoxide. An electron mirror system is employed, similar in principle to that used in the R.C.A. lead-oxide-sulfide tube. It has been reported⁽⁴⁰⁾ that this device has detected bodies only 20°C . above room temperature. It should be added that difficulties are being encountered here in getting the resistance of these thin films down to a suitable value.

V. RECOMMENDATIONS FOR FUTURE RESEARCH

In a detector of infrared radiation the following characteristics are desirable for the majority of military applications:

1. Robustness; i.e., insensitive to shock and vibration.
2. Ease of manufacture; i.e., can be mass produced with uniform performance over a wide range of areas.
3. Normal temperature operation; i.e., should not need to be cooled to a low temperature and should be relatively insensitive to climatic changes.
4. Short response time; i.e., not more than 10^{-3} sec. and preferably less than 10^{-5} sec.
5. High ultimate sensitivity; i.e., its equivalent noise input determined by the normal fluctuations in the surrounding radiation field.
6. High responsivity; i.e., output per watt of incident radiation high enough so that amplifier noise does not determine the ultimate sensitivity of the detector unit as a whole.
7. Freedom from non-linearity and saturation effects.
8. Uniform spectral response; i.e., equal sensitivity to all wavelengths between the visible and 14μ . Even more desirable would be a detector, of which the spectral response could be controlled (e.g., by a filter) so that it responded only to any selected portion of the above spectral range.

The first three qualities are dictated by practical considerations and the other five by scientific considerations. The former are the more essential in that any

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detector which does not have them will involve the Navy in special problems of handling, supply and maintenance which may render the associated equipment unacceptable. The last five qualities are not so essential in that a detector which possesses some of them may be perfectly satisfactory for the solution of certain military problems.

No single detector exists which has all these desirable properties nor is one in sight in the foreseeable future; instead, we have a variety of detectors (some fully developed, some only in the experimental stage) each with its peculiar advantages and disadvantages. Generally speaking, the thermodetectors (bolometers and thermocouples) satisfy the first three practical criteria and have the special advantage that they are uniformly sensitive to all wavelengths. However, they have too long a response time for many potential applications and are decidedly inferior to many photodetectors in ultimate sensitivity. On the other hand, the photodetectors (with the exception of PbS and PbSe) do not satisfy the third of the first three criteria since they have to be operated at liquid air or liquid helium temperatures. However, the photoconductive cells all have very short response times and very high ultimate sensitivity but suffer from the disadvantage that their spectral responses are very limited in range and very non-uniform.

The detector problem may therefore be stated in its simplest form as a question. Should we concentrate our efforts on trying to make thermodetectors faster and more sensitive or should we try and remove the defects of the present photodetectors, or should both lines be pursued? It seems very unlikely that any great improvement can be made in the time of response of thermodetectors, but higher ultimate sensitivity can be obtained by going to low temperatures. So much research has been done on thermodetectors that the fundamental physical reasons for their limitations are fairly well understood. On the other hand, photodetectors such as photoconductors are a relatively recent development and the mechanism of their action is not well understood. This is a field in which the unexpected can still happen, e.g., the discovery that lead selenide has sensitivity to longer wavelengths than lead telluride. It would therefore appear worthwhile to devote considerable effort to research on photodetectors with the object of improving their spectral response in the region between 3 and 14 μ . Whether it will be possible to do this without having to go to very low temperatures is doubtful, but is not yet certain. Even if the detector can operate at normal temperatures, it will have to be shielded from normal temperature radiation by means of a cold enclosure with a cold window of suitable transmission characteristics. However, solid carbon dioxide (dry ice) or liquid air might be adequate for many problems and this would constitute much less of a practical problem than liquid helium.

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Accordingly, the following are our recommendations:

a) The highest priority should be given to increased experimental and theoretical research on the fundamental physical factors underlying the performance (i.e., spectral response, time of response and temperature of operation) of photoconductive detectors. The ultimate objective here is to obtain the nearest approximation to the performance of the lead sulfide cell in the 2.2μ window in the spectral regions of the other atmospheric windows near 3.8, 4.5 and 8 to 12μ .

b) Research on detectors which give a direct picture by absorption of radiation in the spectral range between 3 and 14μ should be emphasized. Of these, the evaporograph appears to be the most promising at present but low temperature phosphors should be investigated and the possibility of some entirely new photochemical process should not be overlooked.

c) Equal emphasis should be given to research on picture forming devices using a scanning process. In addition to present methods, which employ electronic scanning of photoconductive surfaces and thermodetectors, the potentialities of mechanical scanning of small arrays of photoconductive cells should be investigated.

d) Research on bolometers operating at very low temperatures should be continued. Of these the most promising appears to be that being developed by Daunt at Ohio State University.

e) Very low priority should be given to research on thermodetectors which operate at normal temperatures, e.g., thermocouples, bolometers, Golay cells and monomolecular films.

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Part III

THE CHARACTERISTICS OF SKY BACKGROUND

L. Goldberg

The brightness of the daylight sky results partly from the sun's radiation scattered by air molecules, haze, fog, clouds and dust and partly from the selective emission of radiation by air molecules. Below about 3μ the scattered radiation predominates, but at longer wavelengths the selective emission is more important. The night sky brightness, in the absence of moonlight and clouds, is due chiefly to continuous and selective emission by atoms and molecules in the atmosphere. In the visible and near infrared ($0.4\mu - 1.5\mu$) the night sky emission results from the so-called "permanent aurora", whereas at longer wavelengths it arises from thermal emission by molecules.

1. Daylight Sky

a. Rayleigh Scattering

For a given point on the earth's surface, the brightness of the clear daylight sky depends on the coordinates of the observed point in the sky, on the zenith distance of the sun, on the wavelength of the radiation, and on the altitude above sea level. Even in the absence of haze and dust, when the brightness at wavelengths less than 3μ results entirely from Rayleigh scattering by atmospheric molecules, the rigorous calculation of sky intensities from theory is extremely complicated, although not impractical. The necessary formulae have been given by L. V. King⁽¹⁾ and they have been refined more recently by Chandrasekhar⁽²⁾ and by van de Hulst⁽³⁾. The present discussion will be based on approximate formulae, which are adequate for order of magnitude calculations and for illustrative purposes.

According to King⁽¹⁾, the intensity of scattered sky radiation is given by

$$B(z, \psi) = \frac{S}{2\pi} \frac{3}{8} (1 + \cos^2 \alpha) \beta_0 H \sec z, \quad (1)$$

where z and ψ are the zenith angles of the sun and the observed point in the sky, respectively, and α is the scattering angle. S is the flux of solar radiation incident per unit area at the top of the atmosphere. The value of S integrated over

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all wavelengths is 0.136 watt/cm^2 . The quantity H is known as the reduced height of the atmosphere and is defined as the total mass of the atmosphere per unit area above the point of observation, divided by the density at sea level. Its value at sea level is $8.04 \times 10^5 \text{ cm.}$, at 2 km. altitude it is $6.3 \times 10^5 \text{ cm.}$ and at 10 km., 2.0×10^5 . Finally, β_o is the scattering coefficient at sea level and hence $\beta_o H \sec z$ is the optical thickness, frequently denoted by τ . Both S and β_o are functions of the wavelength. According to the original Rayleigh theory

$$\beta_o = \frac{32 \pi^3 (m - 1)^2}{3 N_o \lambda^4} \quad (2)$$

where m is the refractive index of the gas, N_o is the number of molecules per unit volume and λ the wavelength. At sea level and 0°C , N_o is Loschmidt's number = $2.70 \times 10^{19} \text{ cm}^{-3}$. Equation (2) has been refined (see ref. 3) to take account of the anisotropy of the molecules and of the fact that the atmosphere is a mixture of gases, each with its own index of refraction, but the modifications are very slight. The following values of β_o have been computed by van de Hulst from the exact theory:

λ	$\beta_o \times 10^7$
0.3 μ	14.79 cm.^{-1}
0.5 μ	1.75 "
0.7 μ	0.446 "
1.0 μ	0.106 "
2.0 μ	0.0066 "
3.0 μ	0.0013 "

The sky brightness may also be written in terms of the zenith brightness as follows:

$$B(z, \psi) = B(O, \psi) \frac{(1 + \cos^2 \alpha)}{(1 + \cos^2 \psi)} \sec z. \quad (3)$$

Equations (1) and (3) are approximations that hold only for optical thicknesses smaller than about 0.1 and for directions not too close to the horizon, where the path length is proportional to $\sec z$ (plane-parallel atmosphere). In the plane-parallel approximation, the path length in the direction of the horizon is infinite. Actually, the path length at sea level is equivalent to 310 km of air at atmospheric pressure⁽³⁾ (as compared with 8.04 km through the zenith). Multiplying by the appropriate values of β_o , we find that the optical thickness at 1 μ is 0.0085 through the zenith and 0.33 towards the horizon. At 2 μ , the corresponding values are 0.00053 and 0.020. Hence, insofar as the requirement of small optical thickness is concerned, equations (1) and (3) should hold accurately even close to the horizon for all wavelengths longer than about 1.5 μ .

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When the optical thickness is comparable with unity, the emission is no longer proportional to the path length due to atmospheric extinction. If the illumination is assumed to be constant along the path, the sky brightness is proportional to $(1 - e^{-\tau_1})$ (see ref. 3). When τ_1 is very small, the brightness is proportional to τ_1 , and as τ_1 increases, the brightness approaches unity asymptotically. Since the scattering coefficient decreases with wavelength, this has the effect of increasing the ratio of horizon to zenith brightness at long wavelengths. For example, the ratio is about 4 in the blue, 10 in the green and 25 in the red. Beyond 1.5μ , however, the ratio is constant and equal to about 40 (the ratio of air masses). As a result of the extinction, the visual color of the horizon sky is white, but in the infrared, the horizon should have the same "color" as the zenith.

The spectral distribution of scattered sunlight may be obtained by substituting the expression for β in equation (2) into equation (1) and representing S by a Planck function, with $T = 5700^\circ \text{K}$. We obtain

$$B(z, \psi) = \frac{8\pi^3 hc^2 (m-1)^2}{N_0} \frac{R^2}{d} \frac{\lambda^{-9}}{e^{hc/\lambda kT} - 1} H (1 + \cos^2 \alpha) (\sec z) \quad (4)$$

where R is the radius of the sun and d its distance from the earth. Equation (4) gives the sky brightness in units of $\text{ergs cm}^{-2} \text{sec}^{-1} \text{steradian}^{-1}$ per unit wavelength. Inserting sea level values, $N_0 = 2.70 \times 10^{19} \text{cm}^{-3}$, $H = 8.04 \times 10^5 \text{cm}$, we obtain numerically

$$B(z, \psi) = 9.48 \times 10^{-22} \frac{(m-1)^2 \lambda^{-9}}{e^{1.435/\lambda T} - 1} (1 + \cos^2 \alpha) \sec z. \quad (5)$$

Let the altitude of the sun be 30° , and the wavelength 1μ . Then $m - 1 = 2.89 \times 10^{-4}$ and the zenith sky brightness is

$$\frac{9.48 \times 10^{-22} \times 8.35 \times 10^{-8} \times 10^{36}}{11.4} \times \frac{5}{4} = 8.68 \times 10^6$$

in units of $\text{ergs cm}^{-2} \text{sec}^{-1} \text{steradian}^{-1}$ per cm. wavelength. In microwatts per cm^2 per steradian per micron the value is 86.8. This value is of the same order of magnitude as that measured by Butler⁽⁴⁾ at N.R.L. It should be noted from Equation (4) that the sky brightness approaches proportionality with λ^{-8} as soon

as λ becomes large enough so that $\frac{1.435}{\lambda T} < 1$. This occurs beyond about 2.5μ . Numerical values of $B(O, 60^\circ)$ as calculated from equation (5) are given in Table 1 for wavelengths between 0.4μ and 3.0μ .

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Table 1

SKY BRIGHTNESS B COMPUTED FROM EQUATION (5) IN MICROWATTS
PER MICRON PER cm^2 PER STERADIAN

λ (microns)	(m - 1)	B
0.40	2.97×10^{-4}	6966
0.50	2.94	3429
0.60	2.92	1533
0.80	2.90	333
1.0	2.89	86.8
1.2	2.88	26.6
1.4	2.88	9.44
1.6	2.88	3.74
1.8	2.88	1.62
2.0	2.88	0.760
2.5	2.88	0.148
3.0	2.88×10^{-4}	0.0380

b. Approximations in King's Formula

The accurate formulae given by King, to which equations (1) and (3) are approximations, take account of the fact that the sky brightness is not proportional to the path length for large optical thicknesses. They do not, however, allow for the curvature of the atmosphere. In addition, they are based on the following assumptions:

- (1) The scattering particles are smaller than about $1/4 \lambda$.
- (2) Only primary scattering is considered.
- (3) Reflection by the ground and by clouds is neglected.
- (4) Selective absorption and emission by molecules are neglected.

The first assumption is valid in an atmosphere free of haze and dust and undoubtedly holds at altitudes above 1-2 miles. The effect of haze and dust is to increase the horizontal extinction. Also since the scattering by haze and dust is independent of wavelength the blueness of the sky is decreased, especially near the horizon.

King's formula assumes that each ray of light from the sun is scattered only once. Actually, light may be scattered two or more times by the air and may also be scattered by the air after reflection by the ground. The calculation of the secondary scattering is very complicated but is possible as a result of recent work by Chandrasekhar⁽²⁾. Van de Hulst⁽³⁾ has estimated the relative importance of primary and secondary scattering, using Chandrasekhar's formulae.

Using an optical thickness, $\tau = 0.1$, appropriate to $\lambda = 5400 \text{ \AA}$,

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assuming the sun to be at an altitude of 30° , and taking the albedo (ratio of incident to reflected light) of the ground as 0.1, he finds that 77% of the zenith sky brightness is due to single scattering, 15% to multiple scattering and 8% to ground reflection. The albedoes of various surfaces range from about 5% for forests to 65-89% for snow. Cloud-seas may reflect as much as 50-75%. Very little is known of the spectral distribution of the reflected light.

Radiation from the sky is attenuated both by Rayleigh scattering and by the selective absorption of molecules. Equation (4) above assumes that selective absorption is absent. In reality the spectral energy curve of scattered sunlight exhibits the familiar absorption bands of the atmosphere. It is to be expected, however, that equation (4) will hold in the transparent regions of the so-called atmospheric windows. In other words, it should represent the envelope of the spectral energy curve. The selective emission by air molecules will be discussed in the next section in connection with C. P. Butler's measurements. It is negligibly small compared with scattered sunlight except for wavelengths longer than about 3μ .

c. Measurements of Daylight Sky Brightness

Most measurements of daylight sky brightness, made with the aim of verifying Rayleigh's law, have suffered from unfavorable observing conditions (haze and dust) and from the use of too wide a wavelength region. In the main, however, Rayleigh's law has been well verified and should be adequate for most engineering calculations under clear sky conditions.

Tousey and Hulburt⁽⁵⁾ and Packer and Lock⁽⁶⁾ have measured the absolute brightness of the daylight sky from ground level and at various altitudes up to 38,000 feet. The measurements were made with a visual photometer that approximated the sensitivity curve of the eye. It was found by Tousey and Hulburt that the data fitted Rayleigh's theory with a scattering coefficient 35% greater than that computed from the theory. This discrepancy does not seem surprising in view of the wide wavelength range, over which the scattering coefficient varied by a factor of ten.

The Northrop Aircraft Company⁽⁷⁾ has measured the brightness of the sky with a 1P21 blue-sensitive photomultiplier from the ground at Flagstaff, Arizona, and from various altitudes up to 30,000 feet in a B-29 aircraft. The aim was to obtain the response of the photomultiplier to the daylight sky at altitudes of 20,000, 25,000 and 30,000 feet as a function of scattering angle, zenith angle of observed sky, zenith angle of sun and bearing of observed point relative to the sun. The response of the phototube was calibrated in absolute units. The zenith brightness at altitude 25,000 feet was about 40 candles/ft.². This value cannot

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be directly compared with that predicted by theory, owing to the wide and not precisely known wavelength response of the instrument. According to equation (4), the zenith brightness should vary linearly with the reduced height H , and, therefore, nearly proportionally to the pressure (assuming an isothermal atmosphere). An attempt by the Northrop observers to check this phase of the Rayleigh theory was vitiated by thin cirrus clouds at the high altitudes and by large particle scattering in the lower levels. It was found that in general a brightness minimum occurred at a scattering angle of 90° as predicted by the theory and that the brightness distribution at high altitude followed Rayleigh's law for scattering angles greater than 25° . Because of the wide wavelength range employed it is not practical to compare the data with theory in any detail, especially at large zenith angles, since the variation of brightness with optical path at large optical thicknesses is different for each wavelength. The absolute brightness is also difficult to interpret theoretically without detailed knowledge of the wavelength sensitivity curve of the instrument.

A similar set of measurements has been made by Northrop⁽⁸⁾ over the wavelength response region of the PbS cell. It was found that the brightness varied linearly with pressure up to an altitude of 30,000 feet, for zenith angles of 0° and 50° . The angular distribution of sky brightness obeyed Rayleigh's law within about 20% for scattering angles greater than about 35° regardless of the position of the sun or observed sky. For smaller scattering angles, the brightness toward the sun increased much more rapidly than predicted by theory. It was also found that underlying cloud cover can double the sky brightness when observed about 5,000 feet above the cloud layer but that the effect is greatly diminished when the altitude is increased to 10,000 feet above the clouds. Cirrus above the observer can increase the brightness by a factor of four or five over a clear sky.

Very few measurements have been made to check the wavelength dependence of Rayleigh's law in the infrared. Kron and Whitford⁽⁹⁾ found that the sky brightness from Mt. Hamilton, California, diminished between 1μ and 2μ approximately as λ^{-4} rather than nearly as λ^{-8} , as theory predicts. Since the work is unpublished, the extent to which the observations may have been affected by haze and dust is not known.

d. Thermal Radiation

Any measurement of sky brightness involves an exchange of energy between the radiation received from the sky and that radiated to space by the detector. If the measurement is made with a thermocouple, the energy radiated away approximates that of a black body at room temperature. At wavelengths shorter than about 3μ , the radiation from Rayleigh scattering is much greater

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than that emitted by the detector and the net flux is toward the earth. Beyond about 3μ , however, the Rayleigh scattering is negligible and the net flux is away from the earth. For example, from Table 1 we find that the Rayleigh scattering at 2μ is $0.76 \text{ microwatt/cm}^2$, but the radiation emitted by a black body at 300°K is 100 times smaller, or only $0.0078 \text{ microwatt/cm}^2$. On the other hand, at 3μ , the Rayleigh scattering is 0.038 and the thermal radiation 2.9 , in the same units. This means that if the earth's atmosphere were completely transparent in the infrared beyond 3μ , the sky background would have a brightness corresponding to thermal radiation at the temperature of interstellar space, i.e., a few degrees above absolute zero. This elementary picture is modified by the selective emission and absorption of the air molecules. In the region of a highly opaque water vapor band, for example, the emission is that of a black body at air temperature. The net flux at heavily absorbed wavelengths depends on the relative temperatures and emissivities of the detector and the air but roughly speaking the net flux from detector to sky is reduced and may approach zero in the neighborhood of absorption bands. In round figures, about 50% of the infrared energy radiated by the earth is turned back by the atmospheric absorption bands. In the transparent region $9\text{--}11\mu$, however, nearly all the radiation from the earth escapes into space.

A very interesting set of measurements "On the Exchange of Radiant Energy Between the Earth and the Sky" has recently been made at N.R.L. (Washington, D. C.) by C. P. Butler (4). Measurements were made with a Perkin-Elmer spectrometer in the wavelength interval $2\mu - 14\mu$ at several zenith angles as a function of time of day, season and state of overcast. The results agree generally with the picture given above: (1) At all wavelengths from 3μ to 14μ , the net flow of energy is from the earth to the sky. (2) There are no marked diurnal variations in the spectrum of the zenith sky from 3μ to 14μ . (3) The flow of energy is greater in the winter than in the summer. (4) The energy loss is greatest toward the zenith and least toward the horizon, and is also greatest on clear days, less with high overcast and least with low overcast. The heat loss varies from about 50% of the total radiated by the earth on clear days to about 5% on overcast days. (5) In general, the data do not agree with Strong's result that the sky radiation should increase toward the horizon with the square root of the air mass. The increase is less steep than predicted. (6) The absolute energy in $\text{microwatts/cm}^2/\text{micron/steradian}$ lost through the zenith on a clear day in the 10μ window is about 570 as compared with 500 calculated for a black body at 300°K . The agreement is probably within the experimental error. One of Butler's curves, made with zenith sky on a clear day, is shown in Figure 1.

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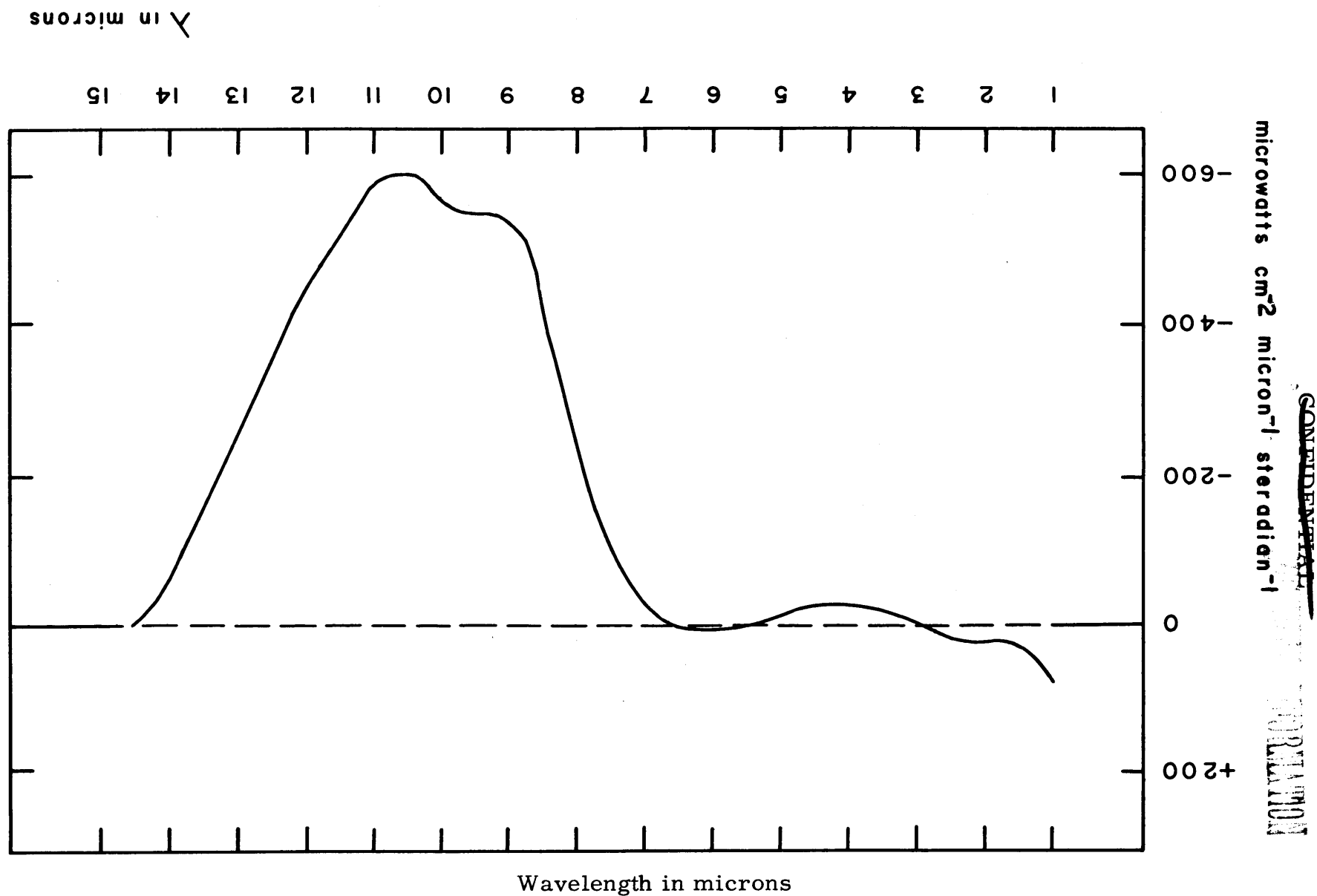


Figure 1. Radiation exchange between earth and zenith sky according to C. P. Butler. Rel. Hum. 60%, Air Temp., 80°F.

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When the curve is above the horizontal line, the flux is toward the earth and vice versa. It will be seen that the "cross over" is at about 3μ , and that the flux is again zero at 6μ , due to H_2O emission. At $9-11\mu$ the atmosphere is transparent but the emission by H_2O and CO_2 returns the flux to zero beyond 14μ .

e. Clouds

Since clouds are formed of relatively large water droplets, Rayleigh's law does not hold, and indeed one would expect, to a first approximation, that the scattering of sunlight by clouds would be independent of wavelength (like that of a white surface), at least in the visible and near infrared. The spectral distribution of light reflected by clouds should, therefore, approximate the solar energy curve without scattering. The sky spectrum on the other hand is proportional to the solar intensity times λ^{-4} . Hence one would expect that the contrast between clouds and sky would be low in the violet, and would increase steadily toward longer wavelengths. This increase of contrast with wavelength is well known and is illustrated in Figure 2, which gives the spectral distribution of unscattered sunlight and sky on a relative energy scale. The curves have arbitrarily been made to intersect at $\lambda 4000 \text{ A}$.

Measurements of cloud droplets^(14,15) indicate that the most frequently occurring diameters are between $10\mu - 15\mu$. Application of Mie's theory (ref. 3, p. 57) of scattering suggests that for particles of 10μ diameter, the scattering varies only slowly with wavelength for wavelengths less than about 5μ . Between 5μ and 10μ , the scattering increases with wavelength to a maximum. Beyond 10μ , the scattering decreases with wavelength and soon approaches a λ^{-4} variation at $\lambda \sim 15\mu$. The only measurements of infrared cloud spectra that have been reported are those recently made by the British at T.R.E., using a

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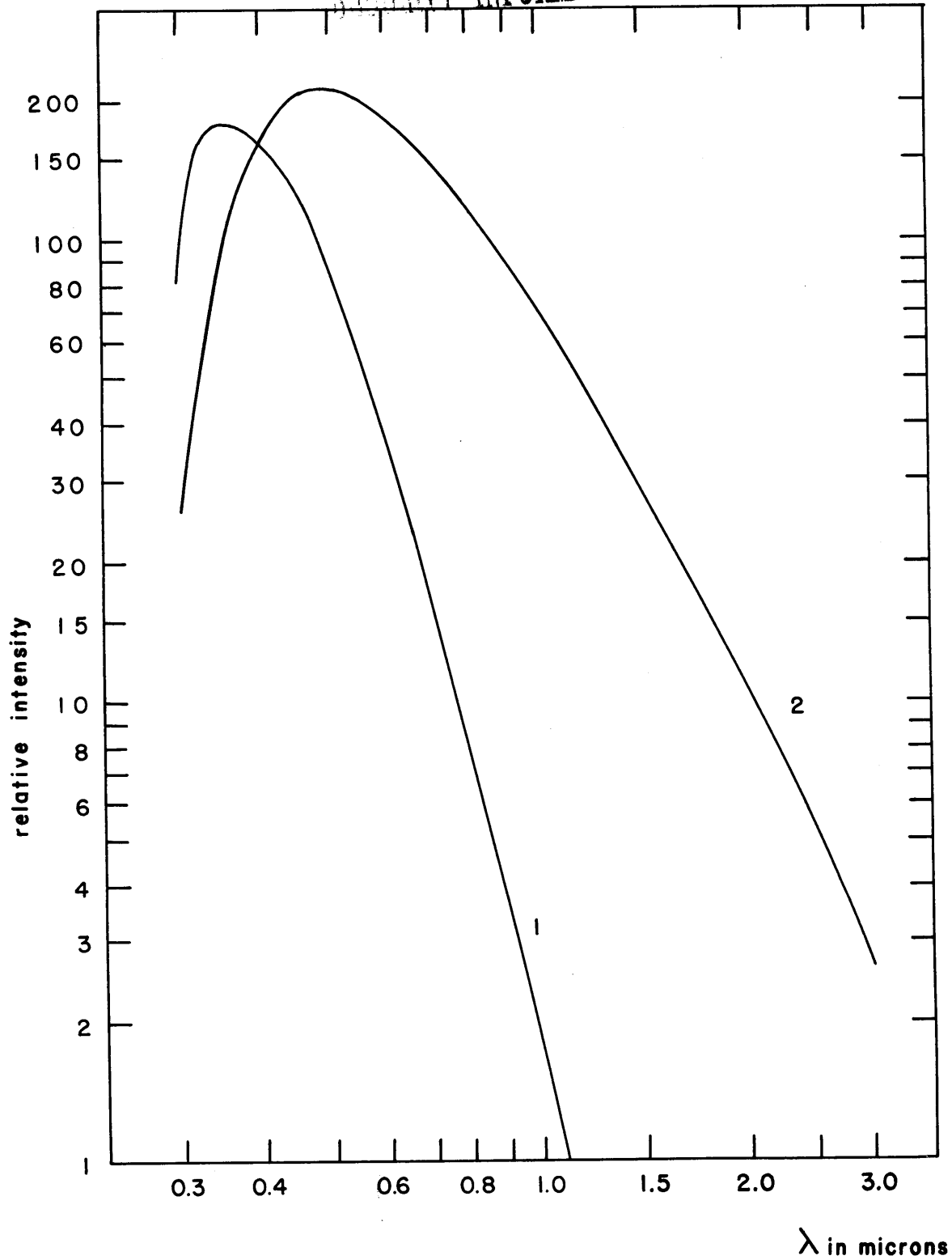


Figure 2. Spectral Distribution of Sunlight.
(1) scattering according to λ^{-4} law and
(2) scattering independent of λ .

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lead telluride cell. They have obtained the interesting result that both sky and cloud brightnesses are essentially zero for wavelengths beyond 3μ , or at least negligible as compared with the radiation from aircraft. The result for the sky brightness is understandable from theory, which predicts a 20-fold decrease in brightness between 2μ and 3μ . However, if the spectral distribution of cloud radiation follows that of sunlight the reduction between 2μ and 3μ would only be about a factor of 4. While it is possible that the cloud particles are smaller than suspected, it should be emphasized that the scattering of solar radiation by clouds is an extremely complicated process and that the theory is still in a primitive state. In any case it is extremely important that the British results be verified experimentally and that a vigorous effort be made to develop a satisfactory theory of cloud scattering. If the British results are correct, the problem of discrimination against clouds would be greatly simplified (see Part IV).

2. Night Sky

The brightness of the night sky in the visible and near infrared is due to emission by atoms and molecules under the influence of particle and radiation bombardment from the sun, the so-called "permanent aurora". At longer wavelengths, beyond about 2μ , the emission is thermal, and differs very little between day and night. The major contributor to the visual brightness is the forbidden line $\lambda 5577$ of OI, with some additional contributions by the D lines of sodium and by bands of O_2 and N_2 . The strongest emission of the night sky is in the infrared at $\lambda 10440$. It was first observed by Stebbins, Whitford, and Swings⁽¹⁰⁾ and has been identified by Meinel as due to OH. No precise intensity measurements have been made on $\lambda 10440$, but it has been estimated as perhaps 10-100 times as strong as $\lambda 5577$. Other strong emission bands occur throughout the near infrared. This suggests that the color of the night sky is infrared and hence that night-time star tracking might be most effective with blue-sensitive cells, especially with filters that absorb $\lambda 5577$ of OI. The evidence seems to be, however, that the total level of the night sky radiation is lower than that of detector noise, which would vitiate this line of attack.

It should also be mentioned that the night sky emission is not uniform but occurs in patchy clouds and fluctuates irregularly in time and position⁽¹¹⁾. The average visual brightness at the zenith, according to Hulburt⁽¹²⁾, is 1.95×10^{-8} microwatt/cm²/sec.

3. Gradients

Reports of measurements of sky gradients appear to be almost non-existent in the scientific literature. The relatively few measurements that have been made have come from laboratories needing the information in connection

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with the development of background discrimination devices. For example, Whitney and Nichols⁽¹³⁾ have carried out harmonic analyses of signals generated by scanning both a point target and the sky with a single 15 degree slit on a disk rotating at 100 c.p.s. The measurements were made from aircraft with a PbS detector. The results are that the signal arising from a small, well-defined image contains harmonics past the 20th, but that the sky wave usually does not contain harmonics greater than the 7th. By suitable choice of slit patterns, the higher harmonics may be enhanced and the lower ones due to sky background suppressed. (See Part IV). The method appears to be successful at all altitudes and in all parts of the sky except close to the sun, where the gradient of sky brightness becomes steep and the proportion of high harmonics increases. The scanning system also fails to discriminate against sharp cloud edges, or against horizon and ground. It would appear to be most important to have available a relatively small number of absolute intensity and spectral measurements in the neighborhood of typical cloud edges.

4. Summary and Conclusions

From the measurements that have been made to date, it seems probable that the rigorous application of existing theories of scattering can lead to accurate predictions of sky brightness provided one is dealing with a pure atmosphere, and knows the reflection characteristics of the ground or underlying cloud cover. Since the atmosphere at low altitudes always contains dust and haze and since very little is known of the reflection spectra of the ground or of clouds, it is doubtful whether these conditions will be realized except at very high altitudes. It should be possible, for very high altitudes, to calculate both the absolute brightness of the clear sky at any wavelength and its angular variation with precision adequate for military application. At low and intermediate altitudes, and in the presence of broken clouds, the accurate calculation of sky brightness is probably not practical. Also, virtually nothing is known concerning the spectral distribution of cloud radiation, apart from the British results referred to above, which must be regarded as highly preliminary. Nor is there any information available on the gradients of cloud edges.

It is obvious from what has been said above that a program of background measurements should be continued. For example, if the British measurements on the spectra of sky and clouds are correct, one of the major problems of using IR in the daytime sky can be solved. However, the number and types of possible measurements are theoretically almost infinite, and it is therefore vital that the program be organized and directed in such a way that the most important measurements are made in the shortest possible time. With this aim in view, the Metcalf Committee proposes the following recommendations:

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1. The Navy should have at its disposal a competent group who are interested in making infrared background measurements, and who will be willing and able to tackle specific problems posed by the various seeker development groups. The group should keep in close touch with other groups that may be making similar measurements in order to avoid unnecessary duplication. An efficient information service such as suggested by the IR Panel, Committee on Electronics, RDB would perform an invaluable service in collecting and distributing reports from the various groups, so that the data could be compared and any important gaps quickly filled in.

2. Provision should be made, preferably within the group, for mathematical analysis and theoretical interpretation of the data in an effort to minimize the number of observations. It is essential that a good man, either within or without any of the existing groups, should study the problem in order to direct the future research intelligently.

3. While it is impractical for the committee to make specific recommendations regarding the actual program, it would like to make the following suggestions:

a. The highest priority should be given to a short-range program for the purpose of answering roughly those questions of immediate urgency in the design of new equipment. For example, the proposed group, had it been in existence, might have undertaken the harmonic analysis of sky radiation that was required for the Sidewinder application. Or, it might now be asked to make the measurements necessary to check the British results on the spectral distribution of radiation from clouds and sky. The problems to be attacked in the short-range program cannot be posed by a committee since they will usually arise in connection with specific instrumentation already designed or built.

b. The group should also engage in a long-range program for studying the general properties of backgrounds under various atmospheric conditions in the hope of unifying the state of knowledge in the field. Again, the most important requirement here is for a first-rate man to suggest the lines of attack.

c. Some standardization regarding the presentation of background data is desirable.

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Part IV

SCANNING SYSTEMS AND COLOR FILTERS

L. I. Schiff

The design of a scanning system, and the decision as to whether or not to use color filters in conjunction with it, must be based on the characteristics of the target and of the background from which it must be distinguished. Particular target and background characteristics have been discussed in Parts I and III, so that only a brief review of them will be presented here. The illustrative examples of the following discussion will be drawn from the air-to-air guided missile problem. This is done partly because of the great intrinsic interest in this application, and partly because somewhat less is known about the IR properties of most land and sea targets and backgrounds than about aircraft targets against sky background. However, many of the considerations presented here and in Chapter 3 in connection with scanning systems and color filters for the air-to-air problem are pertinent to other situations.

1. Target and Background Characteristics

Almost all of the energy radiated in the PbS band by a single-jet aircraft goes into the backward hemisphere. The spectrum is roughly that of a 700°C. black body, peaked at about 3μ . American jets appear to radiate about 3% as much energy close to the forward direction as in the backward direction, whereas British jets give an unobservably small amount forward (less than 1%); the difference may be due to the projecting tail-pipe in the American jets. Most of the infrared radiation from a propeller-driven aircraft comes from the exhaust pipes, the insides of which are at approximately 700°C., although an appreciable amount also comes from the engine housings, which have a larger area but are at a lower temperature (about 200°C). While there is more radiation from propeller-driven planes in the backward than in the forward direction; the difference is much less marked than with jet planes, and in most cases the detection range is roughly independent of aspect.

In the daytime, aircraft may also be detected by the sunlight reflected from them, or by their obscuration of the sky and cloud background. The first of these effects does not occur consistently enough to serve as a basis for a detection scheme; on the other hand, it may confuse the detection system by providing an additional source that is displaced from the engine, and must therefore be considered as a possible liability. The second effect, usually referred to as

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the silhouette effect, can be more important than the engine radiation and will be considered further below. There may also be a characteristic frequency of modulation of the background radiation by the propellers.

It is apparent that even a single aircraft can present a number of detectable signals. Each engine acts as a positive heat source, as does reflected sunlight, and the relative positions and strengths of these signals change as the plane moves. The silhouette acts as a negative source that can change in apparent size and shape.

For air-to-air guided missiles, sky and clouds form the principal backgrounds that have to be considered. When observed at sea level, the spectra of a wide variety of clouds under various lighting conditions appear to be somewhat similar to each other, and to that of the clear sky, except for absolute intensities, between 0.7 and 2.7μ ; there is very little radiation beyond 2.7μ . Further, the clear sky has gradients of intensity, and clouds vary considerably in intensity, size and shape.

2. Functions of Scanning Systems and Color Filters

A successful scanning system must fulfill three functions: sense the target and provide a signal that can be used to guide the missile; avoid being confused by multiple sources in a single target or several neighboring targets; and discriminate between target and background. The scanner may be assisted in these tasks by one or more color filters which transmit different wavelengths of radiation to different extents.

A filter has no effect on the relative intensities of signals that have the same spectral composition, such as the different engines of a multi-engine plane, or neighboring aircraft of the same type. On the other hand, filters can be used to suppress sky background and reflected sunlight by taking advantage of the spectral differences between target and background.

3. Scanning Without a Filter - Night time

A scanning system that is to operate without color filters must make use of the geometrical arrangement of target and background to fulfill the three functions mentioned in Section 2. If there is essentially no background, as is usually the case in nighttime operations, the third function of the scanner is of course unnecessary. The first can be fulfilled by a scanner of extremely simple design in which, for example, the target image is swung around in a circular path (conical scan). If the sensitive cell lies in the center of the circle described by the target image, there is no response; if the cell is off center, a signal is

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produced that has the frequency of the image rotation, and a phase that indicates the correction required to bring it on center. This type of scanner is employed in the AN/DAN-3(XN-1) and the A-4 seekers.

The fulfillment of the second function of the scanner, i.e., avoiding confusion by multiple sources, is difficult to evaluate even in the simple situation just described. No careful theoretical analysis appears to have been made. A few empirical trials have been made with particular scanners; these indicate that the seeker locks on to the heat centroid of the targets at large distances or small angular separations. As the angular separations of the component sources increase, the seeker at first switches in a random manner from one source to another. When only one source is in the field of view, the seeker locks on to it; this is not necessarily the one that was originally the strongest if several of comparable strength were in the field of view. There appears to be no evidence that the seeker fails to lock on to a target because of confusion by multiple sources.

4. Scanning Without a Filter - Daytime

In daytime operations without color filtering, there is always a background due to clear sky or a combination of sky and clouds. With scanners of practical fields of view (1° to 4° diameter), the radiant energy from the background is many orders of magnitude greater than that from the target. Thus even a relatively small gradient in the background intensity can, with the conical scan seeker mentioned above, produce a signal large in comparison with the target signal. A more elaborate scanning system is, therefore, desirable or even essential in this case.

The general approach to this problem that has proven most successful to date can be described in the following way. That portion of the sky-cloud background that is viewed at any instant by the scanner is imagined to be subjected to a two-dimensional space Fourier analysis. If this portion of the background consists of low-order intensity gradients (intensity proportional to a sum of terms that are products of low powers of the two space coordinates), then the Fourier analysis will yield only correspondingly low-order components. The target, on the other hand, shows up as a small region of high intensity, and hence gives rise to localized high-order gradients which are described by high-order Fourier components. The scanning system, then, subjects the field of view to some sort of space Fourier analysis, rejects the low-order components, and makes use of the high-order components to produce the output signal.

A true two-dimensional Fourier analysis of the field of view requires that the intensity of each small element of area of the field be known; the highest-

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order Fourier component that can be determined is then inversely proportional to the linear dimensions of these elements. This information can in principle be obtained "instantaneously (i.e., within the time constant of the detectors) by having a separate sensitive cell measure the intensity of each of these small area elements. An approach similar to this is being considered by Baird Associates. To be successful, cells of quite uniform sensitivity will have to be employed, since non-uniformity will give rise to additional noise (see Chapter 3). An alternative scheme for obtaining a true two-dimensional Fourier analysis is to have a single sensitive cell look at the small area elements in succession, for example by a television-type scan (rectangular coordinates) or a PPI-type scan (polar coordinates). This of course assumes that the field of view does not change appreciably in the total scan time, which cannot be less than the product of the time constant of the sensitive cell and the number of elements into which the field of view is decomposed.

Such a two-dimensional Fourier analysis can in principle distinguish between an illuminated edge or a narrow bright line in the field, and a small (roughly circular) positive or negative source. This is because the latter has high-order Fourier components in any two mutually perpendicular directions, whereas the former has only low-order Fourier components in the direction parallel to the edge. A background discrimination scheme of this type can, therefore, be used to distinguish targets from cloud edges. It would, however, probably be quite complicated, and only somewhat simpler systems have actually been constructed to date.

These simpler systems select the high-order components from a one-dimensional Fourier analysis of the field of view. The dimension involved in most of the systems built thus far is the polar angle of rotation about the center of the field. While such a system will not distinguish in principle between a point and an arbitrarily oriented sharp edge, since both have high-order one-dimensional Fourier components, it is found in practice that discrimination against fuzzy cloud edges is reasonably effective. A particular system of this type (developed at Inyokern for the Sidewinder missile) is discussed in more detail in Chapter 3.

The performance of scanning systems of the types discussed above can be analyzed in terms of two-dimensional filter theory (Elias, Grey and Robinson, Journal of the Optical Society of America, February, 1952). However, such a treatment would require knowledge of the two-dimensional auto-correlation coefficients of the background intensity, which plays the role of noise in the usual filter theory. It would be very laborious to obtain this information in sufficient detail to design scanning systems. Moreover, not nearly this amount of detail is required if the signals to be used emerge from one sensitive cell, or a small

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number of cells. This is because the information available is then essentially one-dimensional in character (i.e., one or a few currents as functions of the time) even though it may arise from a scanning operation on a two-dimensional field. To cite a familiar example, the signal-noise properties of a television transmitter-receiver system can be analyzed by means of the conventional one-dimensional filter theory*even though the image is two-dimensional.

It seems advisable to design the scanning system in such a way as to give the best possible discrimination between target and background when simple assumptions are made concerning the geometrical forms of each. Then the performance can be estimated by working with the noise that is obtained when typical backgrounds are viewed through the scanner.

5. Scanning With a Single Color Filter

A very desirable way to use a single color filter would be to have it transmit only wavelengths longer than 2.7μ , so that the sky-cloud background looks nearly black. Then heat sources could be sensed by means of a simple scanning system without the need for background discrimination. This would provide a good solution if cells were available that would detect radiation longer than 2.7μ with good sensitivity and time constant. While PbSe cells give some promise in this direction, the only cell now available for practical use is PbS, which cuts off at about 3μ . Thus a compromise is necessary, such that the filter cuts off at somewhere between 1 and 2μ , and the PbS cell retains adequate sensitivity. A filter with this property has been made of a thin lead sulfide coating on silver chloride by Eastman Kodak Co.

This will decrease but not entirely eliminate the burden placed on the scanner so far as background discrimination is concerned. For example, a calculation shows that if a filter were to be used that has a sharp cut-off at 1μ , and a simple conical scan (see section 3) of $1/2^\circ$ angular radius were employed with a field of view 4° in diameter, the gradient signal from a typical clear sky background (45° to 90° from the sun) would be roughly equal to the signal from a jet 3 miles away. This 3-mile distance is substantially decreased if clouds are present, or the target is closer to the sun or horizon, or no filter is used.

To just the extent that the sky-cloud background is suppressed by the use of a single filter, the silhouette effect is also suppressed (see Chapter 3). For jet planes at tail aspect, this is not a very serious matter; for example, against

*Given for example by N. Wiener, "Extrapolation, Interpolation, and Smoothing of Stationary Time Series", Wiley, 1941, especially Appendix B by N. Levinson.

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a bright sky (PbS detector and no filter), the positive single-jet source strength is roughly one-third the negative silhouette source strength in a typical case (this ratio is independent of range). Even with a propeller-driven heavy bomber, the corresponding ratio is about one-fifth in a typical case and not nearly as dependent on aspect. However, it must be remembered that shielding of the exhaust stubs of piston engines can substantially reduce the positive source strength of propeller-driven planes. For jet planes viewed from the forward hemisphere, the silhouette effect is dominant in the daytime without filtering. Thus if attacks from forward aspect prove to be operationally desirable, it will probably be important to retain the silhouette effect.

There is some experimental evidence from Baird tracking experiments, which is confirmed by a theoretical analysis, that use of a blue-sensitive cell in place of PbS substantially reduces the contrast between some clouds and clear sky, and thus makes it possible to use the silhouette effect when the background discrimination is only moderately good.

6. Scanning With Two Color Filters

It may also be possible to discriminate against sky-cloud background by making use of the recent discovery at T.R.E., mentioned in section 1, that the spectra of clear sky and of clouds measured at sea level under a variety of lighting conditions are roughly similar, except for absolute intensities, between 0.7 and 2.7μ . (This may not be true at higher altitudes.) Suppose now that the scanning system can be so arranged that radiation from each element of the field is viewed by the sensitive cell through a chopper that is made up of alternate sections of two different color filters. These filters are chosen so that they pass different regions of the spectrum, but in such proportions that the PbS cell outputs are equal when the spectrum is that of clear sky or clouds. Then no signal of the chopping frequency will be obtained from the background. On the other hand, the target will give a signal of chopping frequency, since its spectrum is shifted more towards the infrared and the two filters are not balanced for it.

This system, proposed by S. Jones at T.R.E., should make possible more effective background discrimination than the single filter discussed in the preceding section, when a PbS cell is used, although it would probably not be as good should longer wavelength detecting cells become available. Needless to say, such an arrangement also discards the silhouette effect.

7. Recommendations for Future Work

(a) Practically usable detection cells sensitive to wavelengths greater than 4μ should be developed, so that sky-cloud background can easily be eliminated for targets that are effective heat sources.

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(b) Since the silhouette effect may have to be used for targets that are poor heat sources (such as propellor-driven aircraft with shielded exhaust stubs or jet aircraft at nearly forward aspect), a careful theoretical analysis of general scanning systems should be undertaken with the objective of discovering the simplest possible scanners that can discriminate between target and background on the basis of difference in shape and intensity.

(c) An analysis like that proposed in (b) would be very useful in connection with submarine wake detection and heat-homing missiles that must operate against land, sea, or horizon backgrounds. It would be desirable first to obtain general qualitative data on the characteristics of such targets and background, and then to apply the theoretical scanner analysis to specific problems.

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THE RELATIVE PERFORMANCE OF RADAR AND INFRARED MILITARY DEVICES

E. G. Fubini and C. H. Townes

I. Characteristics

General

A comparison between radar and IR devices is complicated by the different character of the devices both as to the method of detection and as to the transmission characteristics.

The following notes attempt to compare the relative merits of the two techniques from the points of view of (a) range of detection of enemy targets, (b) range of intercept by the enemy, (c) security, (d) resolution and accuracy, and (e) size, weight and complexity.

Propagation

The transmission of radar waves as long as 10 cm. is almost completely unaffected by atmospheric conditions. Waves as short as 1 cm. have very limited ranges in heavy rain, but are not usually seriously affected by fog or light rain. Infrared radiation, on the other hand, cannot penetrate haze or fog much more effectively than can visible light. Under normal haze conditions it may see about twice as far as visible light, but when heavy fog or rain is present, there is essentially no difference in distance of propagation.

Microwaves are absorbed by the atmosphere as is infrared radiation. However, this absorption is generally smaller and can be avoided by a suitable choice of frequency. The only important absorption regions for microwaves are near 1.25 cm. and near 0.5 cm. wavelength. Absorption at 1.25 cm. is a few tenths of a db. per kilometer or less, depending on the amount of water vapor in the air. Absorption near 0.5 cm. is due to O₂ and varies between 14 and 0.03 db/Km., depending on the frequency.

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Range of Detection

(1) Radar

The range of detection may generally be computed with sufficient accuracy from the following considerations:

The power reflected by a target is approximately

$$P_b = P_t \frac{A}{\lambda^2} \frac{r^2}{R^2} \frac{\pi}{2}$$

and the power returned to the radar receiver is

$$P_r = P_t \frac{\pi}{16} \frac{r^4}{R^4} \frac{A}{\lambda^2}$$

Where P_t Power transmitted (Peak power in case of pulses)

R Distance between station and target

r Radius of the radar antenna

λ Wavelength

A Radar cross section of target

P_r Power available at the receiver

B Band-width of the utilization circuits in cycles/sec.

N Equivalent noise power at input of receiver

F Noise figure (input power measured in terms of thermal noise, necessary at the input to obtain unity signal-to-noise ratio at the output)

The received power must be comparable with or greater than N , where $N = k T B F \approx 4 \times 10^{-12} B F$ watts.

As a specific example consider an X band ($\lambda = 3$ cm.) radar detecting a medium-sized aircraft ($A = 3$ square meters). For such a set a typical noise figure F is 20 and the signal power of twice noise may be required for detection. In this case

$$\frac{P_t}{B} = 6.7 \times 10^{-2} \left(\frac{d}{R} \right)^4$$

where $d = 2r$ is the antenna diameter in inches and R is the target distance in statute miles.

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(a) If modulated CW is assumed with a 200 c.p.s. band-width and $N = 8 \times 10^{-18}$ watt then, if an 8.5-mile range is desired, a 5-inch antenna requires a minimum power of 106 watts (more than has been so far obtained with CW tubes). For a 20" antenna the power required is reduced by a factor of 256 so that 0.4 watt is sufficient. This power is easily attainable.

(b) If 2μ sec. pulses are assumed with a band width B of 500 Kc. the peak power required for the same range is 260 Kw. (near the maximum so far obtained) for a 5" antenna and 1 Kw. for a 20" antenna. For a fixed amount of power, the range obtainable by radar increases directly as the diameter of the antenna. As may also be seen from the above formulae, for fixed antenna size the power necessary varies rapidly with the range (as R^4). Thus, if the range R had been taken as 3 miles, instead of 10, the powers given above would have been reduced by a factor of 120.

Experimental results are found to check these computations closely.

(2) Infrared

The power radiated by aircraft or other targets in the frequency range of infrared detectors is dependent on a large number of conditions and is quite variable. For this reason it is difficult to make general statements about range of detection for IR. Detection ranges of 2 to 25 miles on aircraft have been obtained with apertures of approximately 5", but the results depend greatly upon the time of day, weather conditions, aspect, and type of aircraft. (Cf. Chapter 1, p. 5 of this volume.

It should be clear from the examples that ranges of 10 miles against aircraft can be rather easily obtained with ordinary 3 cm. radar provided antenna apertures of 20" or more are possible. For apertures of 5", such ranges are at the limit of practicability while ranges of 3 miles are well within reach. If the wavelength were decreased from 3 cm. to 8 mm., the power necessary for detection would be decreased by a factor of 14, but no change would result in the order of magnitude of difficulty because of the increased difficulty in handling the shorter waves with present techniques. However, when the size of antenna is limited, IR becomes relatively more favorable. Thus, if favorable weather conditions are assured, detection of aircraft at 10 miles with the use of 5" antenna or mirrors is very much simpler by infrared techniques than by radar.

Security

Passive infrared cannot be intercepted, whereas freedom from intercept is difficult to obtain in the case of radar. This presumes, of course, that the

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enemy is equipped with effective intercept receivers covering the frequency band employed by the radar. Such an assumption may not always be realistic; for instance, the construction of intercept receivers in the range above 12,000 Mc. is in its infancy even in this country. The range at which radar can be intercepted is discussed below.

It must be emphasized that the ability of the enemy to intercept our signals is not always significant. In the case of ground radar the interception by the enemy of our radar signals is not important in many cases.

Range of Intercept

The computations of the range at which enemy radars can be intercepted can be summarized by stating that, if the enemy's frequency is known approximately, the sensitivity of receivers with present day techniques is such that only line-of-sight considerations will limit the range. The problem is more complicated, of course, if the frequency is not known and if scanning techniques need to be used.

It is important to consider the effect of atmospheric absorption on the detection and intercept ranges. The intercept range can never be made less than twice the detection range of the radar, no matter how great the atmospheric absorption, and in practice is always considerably greater. It will be easily found that in order to use the absorption to decrease the range at which a radar can be intercepted, it is necessary to waste a great deal of power. Consider, for instance, the case of two wavelengths very close to each other, one without attenuation and the other with an absorption of 10 db./Km. The returned signal for the former from a target at a distance of 10 Km. is the same as that returned to the latter from a target at about 1.5 Km. At 10 Km. the signal of the highly absorbed wavelength is 100 db. down from its free space value and the chances of intercept by an enemy are, therefore, very slim. On the other hand, this advantage has been bought at the high price of reduction in useful detection range from 10 to 1.5 Km., a ratio of about 6. In other words security from interception for the case of a two-way system like radar is bought at a high price.

The situation is radically different in the case of one-way communication (or transponder - beacon) systems. In these it is possible to design the system without too much loss in power so that, at the maximum desired distance, the margin over noise is a minimum, say 10 db. The range at which intercept is possible can be made to be only slightly greater than the maximum range of the equipment.

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For instance, let a maximum communication range of 10 miles be desired, and the frequency be chosen so that the atmospheric absorption is 2 db./mile. Such an absorption can be found in the oxygen absorption band near 0.5 cm. wavelength. Then the system will be designed with 20 db. more power than that required for the case of free space and with a safety factor of, say, 10 db. over the minimum necessary. The range at which intercept is possible will be about 14 miles, or only 40% greater than the maximum useful range of the system.

Jamming

The importance of jamming in a comparison between radar and infrared should not be overemphasized. While radars can be jammed and deprived of range information on the jammer, they can often determine its direction. The effectiveness of "window" depends greatly upon a variety of operational conditions and the training of the operators. Details of this and of the wide variety of other types of radar countermeasures are too complex to be discussed in this report. Suffice it to say that radar jamming is not a simple problem and that susceptibility to jamming or deception should not in general be considered a primary factor in the comparison with infrared. Infrared has difficulties in many ways equivalent to jamming since it is inoperable under a wide range of weather conditions and certain types of background. The enemy could frequently pick conditions under which IR is ineffective. Picking such conditions will impose tactical limitations which will often be comparable to those imposed by the use of radar countermeasures.

It should be noted that infrared devices used for the purpose of defense generally suffer more heavily from poor functioning due to bad weather or background than do those used for attack, since an attacker can to a certain extent choose the conditions of attack, whereas a defensive weapon may be needed during any weather conditions.

Rate of Search

The rate of angular search of an IR set is limited by the time constant of the system. This time constant can never be made smaller than that of the detecting cell, which for an average PbS is about 0.2 milliseconds. With such a cell about 5,000 elements of solid angle can be explored per second. This is approximately 15 times faster than the rate of search of a radar with a pulse repetition frequency of one thousand per second assuming 3 pulses per target are necessary for detection. It must be remembered, however, that an infrared set with a time constant as short as 0.2 milliseconds (band-width ~1,000 c.p.s.) is assumed and that such a set will have a range of detection which is less by a factor of ap-

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proximately 3 than that of the usual type with a band-width of about 100 c.p.s. Another factor in favor of IR systems is that a mosaic of cells can be used more easily and with a larger number of elements than the number of beams in a radar. Hence, it appears that in general the rate of angular search of an IR set will be greater than that of a radar. When bolometers or thermopiles are employed, the maximum rates of angular search will be decreased by factors of 10 to 50, but still are comparable with rates of search by radar. On the other hand, the rate of search of an IR device scanning the surface of the ground or sea from a plane is much slower than that of a radar which can use range discrimination to distinguish between the different elements of the ground.

Bearing Resolution and Accuracy

The bearing resolution of a detection device can be defined as the ability to discriminate between the directions of two adjacent objects. Bearing accuracy on the other hand can be defined as the ability to measure with a minimum of error the direction of an isolated object.

The resolution of a radar or IR device is measured by its beam width. The accuracy can be increased by suitable means (for instance, conical scanning) over and above the angular resolution.

A basic advantage of infrared devices is that their resolution is independent of the size of the lens. The resolution of infrared devices is almost never limited by the size of aperture and consequent diffraction patterns. It is usually determined by the size of the elements of the detector and the focal length of the lens, both of which can generally be varied to give any resolution needed. An angular resolution of 5-10 mils is easily obtained. In a radar on the other hand the angle which can be resolved is inversely proportional to the size of the antenna, and is in general poorer than for an infrared device. For these reasons infrared devices are particularly effective when resolution is required with small apertures. This advantage in resolution of IR devices is an important one. In some cases even the minor lobes of radar beams may give interfering signals from strong reflectors such as the ground, and hence, give effectively no angular resolution. Thus an airborne radar with a small antenna may have difficulty seeing anything other than the ground at ranges greater than its altitude. IR is, of course, free from this particular difficulty.

From the point of view of accuracy the difference between radar and IR can be considered as a sensitivity problem. In radar, lobe switching can increase the accuracy to a fraction of the resolution (beam width) about equal to the available noise-to-signal ratio. Thus, with a 20" dish at X band the resolution is about 1° or 17 mils and the accuracy can be made equal to 2 mils pro-

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vided a S/N ratio of about 10 db. is available at the receiver. However, for objects of finite size at close range the angular accuracy is limited by the so-called glint effect (variations in the apparent position of the target which depend on the angle of view). Infrared devices are relatively free from glint and can be made to give setting accuracies much greater than the resolution, but for usual designs the setting error is about one half the minimum angular resolution.

Millimeter Waves

Wavelengths in the millimeter range are in many respects intermediate in properties between infrared and normal radar. In certain applications they would have the advantages of both radar and IR (and in some, the disadvantages of both). Although millimeter waves would be more limited by rain and clouds than is ordinary radar, they could penetrate haze or light fog fairly well. If millimeter wave techniques are developed in the future, they will change some of the conclusions contained here by alleviating some of the difficulties with present radar.

Weight, Size and Complication

Comparison between weight, size and complication of IR and radar sets which perform similar functions is made difficult by the following considerations:

(1) Since radar can give range and velocity of targets, such data are usually required and built into present radar sets. If only the directional information provided by infrared is required, some of the complications of these radars are unwarranted and should not be included in the comparison. Unfortunately no direction-only radar with useful range of 5-10 miles has been built and comparisons must be based on a controversial guess.

(2) In comparing weights of radar and IR equipment one must resist the temptation to expect additional information and performance from radar sets which are not expected of their infrared counterparts.

Radars meeting full service specifications but built with due attention to weight and size reduction are available. On the other hand, IR airborne sets are only in the developmental stage. Weights and sizes are, therefore, greater than those which can eventually be obtained (with better engineering) and smaller in another respect (because no attempt has been made yet to meet vibration, shock and climatic specifications).

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If the above reservations are kept in mind, some examples of actual equipment may give a useful comparison. The weight of one of the most elaborate radar AI sets (APT3) in production today is 300 lbs. This set includes both search and tracking functions. The weight of a future tracking set (with no search but including a small radar for range determination) is estimated to be 175 lbs. (Gen. El. Report R650 L 197-7). The weight of a future airborne IR search set with no tracking is estimated to be 125 lbs. This may be compared with a modified APT3 radar capable of both directional search and tracking but with all range information eliminated which is estimated to weigh 200 lbs., or 100 lbs. less than the full set.

Aircraft detecting devices for use in missiles of ranges between 2 and 8 miles have the following characteristics.

- (a) The Glenn Martin DPN9 is an active X band pulsed radar. It has 50 Kw. power, a 5" horn, it weighs 57 lbs., has an 11" diameter and is 26" long. It contains 110 tubes.
- (b) The Ryan seeker is a direction-only, CW radar at X band with 6 watts power and a 5" dish. It is 8" in diameter, 15" long, weighs 30 lbs., and contains 90 tubes.
- (c) The DAN-3 and Sidewinder seeker are infrared seekers which have 5" diameters, are about 12" long, weigh about 15 lbs., and contain 12 and 5 tubes respectively.

Despite all the uncertainties involved, an attempt will still be made to guess the relative size, weight and complications of comparable IR and radar sets. It is to be reasonably expected that IR sets will have about half the weight of comparable radar sets and will require half their space and primary power. Perhaps a more important advantage than the smaller weight and size of IR is the reduction in complication, cost and maintenance difficulty to be expected. An IR device would probably have 1/3 as many tubes as its radar counterpart.

II. Military Uses

Most of the possible military uses of infrared fall under the following classifications:

- 1. Search and direction finding
 - a. Ground based
 - b. Airplane based
 - c. Ship based
 - d. Submarine based

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2. Range Measurements
3. Communications, including IFF
4. Air Navigation and Reconnaissance
 - a. Absolute positioning
 - b. Contact navigation
 - c. Reconnaissance
5. Gun directing, including bombing
6. Homing missiles
7. Viewers

Each of these categories is discussed separately below. An attempt is made to compare the cost and performance of IR with that of radar and to outline the conditions under which IR devices may be valuable to the armed forces. These considerations are based to a considerable extent on the general comparison of IR and radar above, and some of the arguments will not be repeated.

1a. Search from Ground Based Stations

(1) Range: A large radar installation can detect fighter planes at 90 miles with surety and larger planes at 120 miles. A corresponding figure for IR of 8" aperture is not much more than 25 miles under good conditions (night-time and clear weather), and for some types of planes head-on, it may be as small as 1 mile. Of course, larger apertures can be used to increase range on absolutely clear nights, but visibility of more than 25 miles may be so rare as to make this potentiality of little value. Daytime ranges are considerably less than those at night.

(2) Reliability under bad weather conditions: L-band (20 cm.) can be used reliably almost all of the time, whereas IR would be made inoperable by clouds a large fraction of the time in many localities.

(3) Size: A large radar installation would be larger than an IR system, but for ground-based stations this is seldom a great disadvantage. Furthermore, if a radar giving directional information only and range performance comparable with IR were desirable, it would be considerably smaller than present radar search systems.

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(4) Information Yielded: Radar gives valuable range information in addition to direction. For isolated airplanes the radar will give angular position as accurately as IR. For a group of planes, the higher resolution of IR would be of some advantage in isolating individual targets. IR may give better angular accuracy also for low-flying airplanes when the ground interferes with propagation of the radar waves. It is not known whether IR can successfully detect jet aircraft at low altitude against the large gradients of radiation intensity near the horizon but it has been shown recently that detection of propeller modulation can be successfully used to discriminate against background for propeller-driven aircraft.

Propeller modulation or MTI (Moving Target Indicator) devices would permit detection of low-flying aircraft by radar also, but these will still not allow accurate determination of angles of elevation comparable to the beam width of the antenna.

(5) Countermeasures: Ground radar may be more easily jammed than can IR. However, under most of the conditions when jamming of ground radar is carried on by attacking aircraft the radar will still give directional information on the jammer.

(6) Security: Although passive IR devices would avoid the possibility of intercept which is present for radar, this advantage can hardly outweigh the considerable loss in performance since detection of ground stations is usually not of primary military importance.

In conclusion, ground based IR search devices may be justifiable only for location of low-flying planes, where they may be useful in conjunction with radar to determine altitude, or in exceptional cases (perhaps in polar regions) where large radar installations are impractical. Investigation of location of low-flying planes is apparently being undertaken by Project Lincoln, and should be valuable.

1b. Search from airplane

The greater range, speed in searching a plane surface, and all-weather performance of radar make it better than IR except in special conditions, which are:

(1) Search for Submarines: This will not be discussed here, since it is considered in Chapter 4 of this volume.

(2) Search for surface vessels where plane does not want to be intercepted: Since large surface vessels are good infrared targets, they have been

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detected at distances as great as 10 miles by relatively small IR systems, and may be detectable from an aircraft at somewhat larger distance. If a sneak attack on a large ship during a clear night is to be made maintaining radar silence an infrared search device could profitably be used. This would be a rather specialized use, and may not be of great importance to the United States since enemy surface ships will not be plentiful. Detection of ship's wakes may also be useful in search, but this is closely allied to the submarine problem, and will not be discussed here.

(3) Search for airplanes

- (a) Tail-warning devices - IR tail warning during the day is not very useful because of the large number of false alarms which will be produced by signals from the sun, moon, ground, sea, and clouds. Future research may decrease the importance of some of these limitations and in straight and level flight IR tail warning could still be of some value since the false alarms will stay relatively fixed in direction. At night, if the enemy uses radar AI, then a crystal video intercept receiver would be preferable because it can see through clouds and is not much heavier than the corresponding IR device. However, if the enemy can make effective use of an infrared AI set (without radar range information), a simple IR set may possibly be useful for tail warning. On the other hand, the head-on aspect of many aircraft may supply insufficient radiation to give enough range of warning.

In conclusion, IR tail-warning devices are of doubtful usefulness, although they might be developed with low priority so that they will be available in case situations arise where radar tail-warning devices are ineffective. In any case, an IR tail-warning device seems to have no major advantage over a radar system unless requirements on its performance are kept low enough that it can be made considerably simpler and lighter than a radar set. Present IR tail-warning developments should be examined with this in mind.

- (b) Wide angle search - A wide angle search device based on IR principles can be made superior in some respects to the human vision and, except for the usual weather limitation, appears to have advantages. The speed of search of a given solid angle by IR devices is comparable with, and may be greater than, the speed of radar search. Even though IR

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search from planes is subject to the usual weather and background limitations, it may be useful due to the following factors:

- (i) Small size and weight as compared with radar and the small aperture required in the airplane
- (ii) Freedom from intercept
- (iii) More freedom from jamming
- (iv) Freedom from ground return in minor lobes
- (v) Fast rate of search.

For airborne equipment (i) and (ii) are much more important than for land based instruments.

One of the more useful applications of IR search from airplanes would seem to be interception of aircraft at night. However, the lack of range information may seriously interfere with the usefulness of such a device, and the addition of range-only radar would destroy to a considerable extent advantages (i) and (ii).

In conclusion, a clear case for or against the usefulness of IR search systems in airplanes cannot be made at present.

1c. Ship-based search

Most of the considerations of (1a) apply here also except for:

(1) Security: In the case of ships, security from intercept may be very important in some cases. Radar silence may be so vital as to prevent the use of radar even at millimeter wavelengths, which might be intercepted at ranges of the order of 20 miles or more. In those cases infrared search devices, despite their intrinsic weather limitations, may become important as a last resort defense weapon against airplanes.

In conclusion, ship-to-air search devices based on infrared techniques should not be discouraged. Ship-to-ship IR search is of less importance, and can probably be adequately done with any device which is good for ship-to-air search.

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1d. Submarine-based search devices

An infrared search system located in the periscope of a submarine can take advantage of such characteristics of infrared as small power, small size, passivity, and accurate directional measurements. Security or radio silence is extremely important. In addition, small size is very valuable because of the limited size of the periscope. The general characteristics of such an infrared finder and directional element would be about those of visual observations with less detail in the picture and less accuracy in the range. It would be blacked out by essentially the same type of fog or rain conditions that would black out visual observations. However, the infrared would extend these types of observations to include night-time. An infrared search system may also serve as a warning to the submarine of the approach of enemy aircraft. For ship detection, an IR system seems to have ranges comparable with, and greater bearing accuracy than, present passive sonars.

In conclusion, infrared search devices to be mounted in submarine periscopes would supplement present detecting systems and should be given some priority if it is expected that any significant number of attacks on enemy shipping will be made by submarines.

2. Range measurement

A radar for "range only" measurements would be of essentially the same size as a light-flash ranging device (of the type being developed by Farrand Opt. Co.). The range accuracy obtained is essentially the same for both systems - of the order of 10 feet. The radar can be made to operate at longer ranges. The range of the optical system for an airplane seems to be limited to about five miles at night and two miles in the daytime. This is independent of whether the airplane is a shiny or diffusive reflector but would not be true, of course, for a plane painted black. Radar also has the advantage of being able to see through fog whereas the optical system is good only in fair weather. The optical system would, unless filtered to produce infrared only, give position away at night so badly that it will probably not be used at night. However, it could be filtered and infrared used with reduction in range by approximately a factor of 2. The radar system is fundamentally more difficult to countermeasure because it responds over a limited frequency range. However, the optical system would have a factor of surprise and countermeasures might not immediately be developed. It could be counteracted fairly easily, however, by means of a searchlight or landing light or perhaps even a navigation light. The one big advantage that the optical system has is directivity. Its beam width is approximately $1/6^\circ$ as compared with about two degrees for a radar system of the same size. This would allow ranging on a single part of a complex target. This directivity would not be of

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great advantage for use in bombing ships; on the other hand, it might be of considerable advantage in bombing or shelling land targets which are not themselves good radar targets (e.g., tanks or trucks). For large installations the optical pulse device seems to have no advantages over direct triangulation. In fact, the triangulation is considerably simpler. However, for easily portable land weapons, and especially for airplane use, the short base lines available and the difficulty of pointing accurately would probably make the pulse system better.

Two special types of IR triangulation devices deserve attention. One involves location of guns which use flashless powder at night. Although this powder gives little optical flash, it must give a sizeable amount of infrared radiation which can be used, much as the visible flashes have been used in the past, to locate gun positions. Triangulation to determine the position of the heated barrels of large guns at night also seems possible. Radar can locate mortars by detecting mortar shells in flight, but it is not suitable for locating more distant guns or the origin of shells with a rather flat trajectory.

In conclusion, because the light-pulse device is unique in picking out the range to a small part of a complex target, exploration of potentialities of this device should be continued.

3. Communications, including IFF

Many IR communications systems have been developed and are in the hands of the services for evaluation or use. Because these systems are available, and their problems more or less straightforward, detailed consideration of IR communications systems by Project Metcalf seems unnecessary. On the other hand, infrared IFF has received less attention and is less well-developed.

The IFF problem has not been considered very fully. However, it does seem clear that a plane-plane IFF system using an IR beacon would have advantages. A complete radar IFF system has difficulties for lack of directivity. The lead plane in a flight may attempt to interrogate a plane ahead, and receive beacon responses from other planes in its own flight because of the backward-directed minor lobes of its antenna. An IR beacon interrogated by radio and viewed by an IR detecting device would allow precise directional determination of the responding beacon, and hence prevent confusion of the IFF. The weight and complexity of equipment involved in the IR system should be comparable with those of a radio system.

In conclusion, plane-to-plane IFF using a combination of radio and IR is superior to IFF using radio-frequency waves only but it is subject to weather

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limitations. It should be useful for short range in air-to-air and ground-to-air uses. The operational importance of these applications should be evaluated.

4. Air navigation

We shall distinguish two types of navigation: (a) absolute positioning without reference to signals from terrain below, and (b) contact navigation from recognition of signals from the terrain below.

(a) The "star tracker" is a device which gives absolute positioning with the use of a vertical, which would presumably be a gyroscope. It may use either optical or IR radiation. This allows very long-range navigation (at high altitudes or when clouds are not present) with an accuracy determined primarily by errors in vertical. Verticals which are accurate to $1/4^{\circ}$, or 15 miles on the earth's surface are now available, and considerably better verticals may be developed. Such a device could be used to position a very long-range missile. There is no radio device which competes with the star tracker. All radio methods for positioning a long-range missile, such as Loran, are very susceptible to counter-measures.

In conclusion, the star tracker has little or no competition from radio techniques for absolute positioning without reference to terrain.

(b) The usual type of navigation by radar makes use of a combination of some dead reckoning with recognition of terrain on a radar screen. Radar does not see quite as much detail as can be seen with an infrared scanning device, but it has a longer range, and gathers information more rapidly. IR scanning is limited to a range of about twice the altitude, whereas radar covers a range of about 50 miles, or about 100 times the area scanned by IR. Radar can cover this large distance almost regardless of altitude partly because it discriminates between objects at different ranges. For any device which can only discriminate angle such as IR, objects at longer distances tend to all merge together in the horizon. Radar covers the large area in the same time that IR is covering the smaller area. Hence, for navigation purposes radar is much superior. In addition, it is relatively unaffected by clouds. Usually there is no need for radio silence during navigation, since flights over enemy territory will almost certainly be known to the enemy through its own radar.

In conclusion, IR should not be considered for contact navigation.

(c) Reconnaissance: IR sees hot targets such as a powerhouse, heat-producing factory, etc., while radar can see most clearly boundaries between land and water, bridges, and isolated large buildings. Because the two techniques

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see different targets, IR scanning systems may be of use over land for reconnaissance even though they are not of such help in navigation. IR may be more effective than visual observation in locating certain types of camouflaged factories. For daylight observations through light haze IR will also see about twice as far as the human eye.

A measure of the effectiveness of IR in locating power plants is given by observations on Manhattan Island. A 4.5" aperture IR scanning system with a thermistor detector was flown over Manhattan at night at an altitude of about 5,000 feet. The results obtained are shown in Fig. 1, together with those obtained in a similar daytime test. The major avenues in Manhattan could be clearly picked out by IR, as well as the outline of the island. Eight very bright spots showed up. Five of these were power houses, and include all of the major power houses located in Manhattan. The remaining three bright spots were not definitely identified, but seem to be mostly due to industrial establishments.

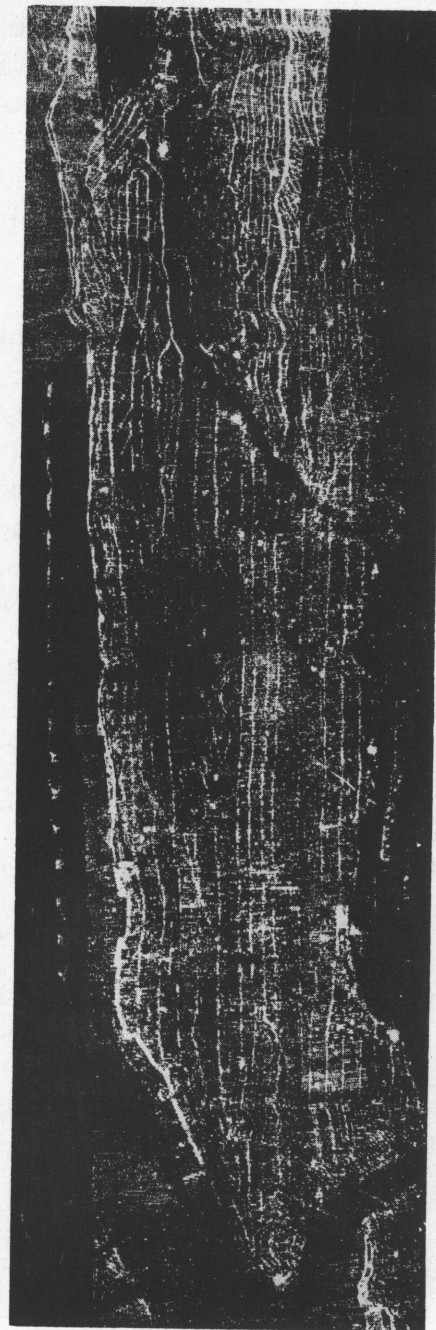
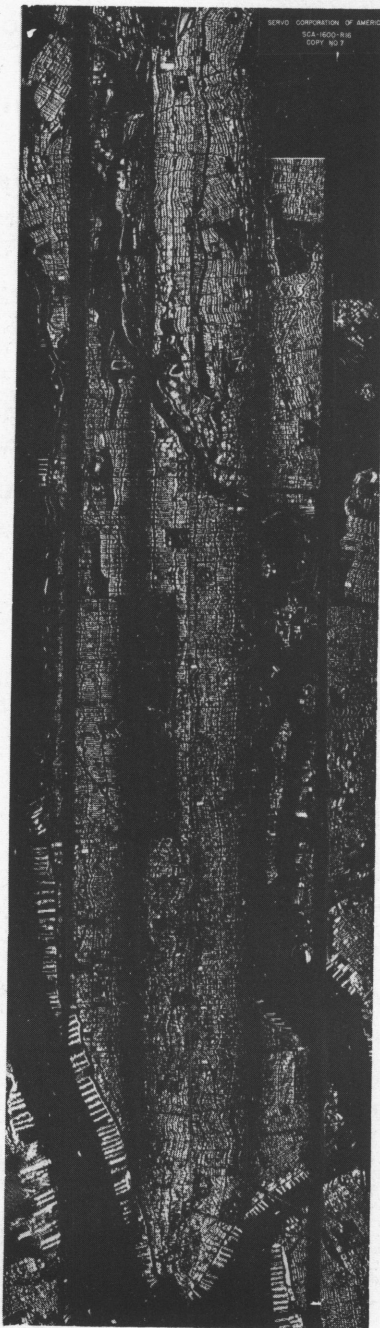
Reconnaissance with passive radar which will measure differences in temperature or in emissive power at wavelengths of a few millimeters may also be used. (Report of Beacon Hill Study Group to be printed, Detection of Thermal Radiation at Microwave Frequencies, W. A. Craven and R. H. Genoud, Hughes Aircraft Co., Feb. 8, 1951.) The prime advantage which this has over infrared reconnaissance of the same general type is that the longer waves would penetrate haze. In this case the microwave devices would not see any farther than IR in clear weather because there is no range discrimination. IR would have the advantage of a very much smaller antenna. In addition the IR could probably search faster for the following reasons:

- (i) Fundamental considerations show that suitable IR devices can in principle detect a small difference in temperature enormously faster than can microwave devices. Actually, IR detectors are very far from reaching this type of ideal performance and any quantitative statement of the relative speeds of realizable IR and microwave devices in detecting temperature differences is very difficult because of the lack of extensive development and tests with this in mind. However, remembering the above difficulty, it is estimated that a single IR detector can be made to detect small temperature differences approximately ten times faster than can a microwave detector.
- (ii) It is considerably easier to put multiple receivers or detectors in an IR optical system than in a radar antenna.
- (iii) Apparent temperature differences are probably somewhat larger over land in microwave region than in IR because of the large differences in emissive power for microwave. This difference is probably less than a factor of 10, however.

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FLIGHT TEST - MANHATTAN ISLAND - AID TO NIGHT



THERMAL MAP TAKEN DURING DAYTIME

ALTITUDE	3000 FT.	WEATHER	CLEAR
SPEED	165 MPH	TIME	1000
V/H	4.2% SEC.	DATE	21 JULY 1951

THERMAL MAP TAKEN AT NIGHT

ALTITUDE	5000 FT.	WEATHER	CLEAR
SPEED	150 MPH	TIME	2200
V/H	2.5% SEC.	DATE	31 JULY 1951

SERVO CORPORATION OF AMERICA NEW HYDE PARK NEW YORK

Figure 1 - Thermal Map of Manhattan.

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Although IR devices appear to be faster than radar in thermal mapping, and would also be smaller, it is important to remember the great advantage microwaves have in penetrating haze. Both IR and millimeter wave devices would seem to be worth investigation, and they would probably show up different types of targets.*

In conclusion, both IR and millimeter passive devices for reconnaissance may be useful, and the characteristic radiations of these types from land targets should be explored.

5. Gun directing, including bombing

IR tracking devices for air-to-air combat would be preferable to radar tracking primarily in those cases where a combined search-track equipment is needed, and where IR search is desirable for some of the reasons mentioned in the section under search. In such cases IR tracking would be lighter and smaller without introducing operational limitations not already present for IR search. It is assumed that the IR tracking and search optics can be combined and that

* In principle, IR techniques should detect a small difference in temperature enormously faster than can microwave techniques. The theoretical ratio of times required is

$$\frac{t_{mic}}{t_{IR}} \approx \frac{A \sigma T^3}{k \Delta \gamma} \approx 10^6$$

where A is the area of the IR detector, which is assumed to be 1 sq. mm.

σ is the Stefan-Boltzmann constant

T is the absolute temperature

k is the Boltzmann constant

$\Delta \gamma$ is the band-width of the microwave receiver,
assumed to be 10^4 Megacycles/sec.

IR is faster not only because the effective band width is much larger so that more energy is received, but also because the dimensions of the IR detecting elements are many wavelengths, and hence they act as a large number of independent receiving elements of the microwave type, giving better averaging of signals.

Actually the time required for IR detection is limited by the time constant of the detector, which may be a few milliseconds. With sufficiently strong signals, the time for detection may be less than the time constant of the detector, but usually by not more than a factor of 10. The time required for actual microwave detectors is given by

$$t \sim \left(\frac{T}{\Delta T} \right)^2 \frac{F^2}{\Delta \gamma}, \text{ where } \Delta T \text{ is the temperature difference to be}$$

detected, and F the noise figure of the receiver. A typical effective temperature difference ΔT can only be guessed, but assuming $\Delta T = 10^\circ$, $T = 300^\circ \text{K.}$, and $F = 200$ over a band-width $\Delta \gamma$ of 10^{10} cycles/sec., the above expression gives $t = 1/300$ sec.

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where necessary a small radar ranging device can use essentially the same optics.

IR should be of some use in bombing ships, although reflections from waves seem to have given too many competing signals in the past when bombing airplanes view ships at angles near the vertical.

Because IR sees a different set of targets than does radar as noted above, it should be useful as an adjunct to radar in bombing land targets when no good radar landmark is in the immediate vicinity. This would apply, for example, to bombing a city which is not located on a river or lake which normally provide the best radar reference points. An airplane would have to locate its target approximately by radar, and then IR might be used to locate a power house or factory to be used as aim point.

In conclusion, IR tracking will be useful only under special conditions. IR may be useful as an adjunct to radar in land bombing at night with no overcast. Characteristics of land IR targets should be explored.

6. Homing Missiles

IR is very well suited to guide certain types of homing missiles. In these cases the light weight and cheapness of an IR seeker and the small size of the aperture (or mirror) required are particularly important. The discussion of Range of Detection above shows that with a 5" dish antenna, an 8-mile range on a jet aircraft is very difficult with an active radar missile. This range is not difficult, however, with an IR seeker under favorable conditions of weather and plane aspect. Small homing missiles with diameters less than 5" would put radar at a still greater disadvantage. An active radar missile with a small antenna can also be expected to encounter difficulties with reflections from the ground of radiation emitted by side lobes, which may make it impossible to home on to an aircraft at a distance greater than the missile's altitude. Semiactive radar does not have as much difficulty from the small size imposed by a missile, but of course requires equipment in a mother plane or the equivalent and imposes certain tactical limitations. A fuller discussion of certain types of homing missiles with infrared guidance is given in Chapters 3 and 5 of this volume.

It is possible that infrared guidance could be used in missile to missile combat. Here, in addition to the advantages of small aperture and size discussed above, IR has an important additional advantage over radar in the strength of target. The radar cross section of a supersonic missile is rather small, particularly for head-on or tail aspects, so that radar detection at sizeable distances would be particularly difficult. Most supersonic missiles would be strong IR

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emitters, however. In addition to IR radiation emitted as a result of combustion, considerable heating of the missiles due to air friction occurs, so that skin temperatures as high as 600°C. may be expected.

7. Viewers

Viewers employing infrared illumination have been fairly widely used and are familiar enough to the Armed Forces that no discussions of their military potentialities seem necessary here. They are also reviewed in Chapter 6 of this volume.

Present viewers cannot normally be used passively (without illumination) because they are not sensitive to the longer IR radiation emitted by objects at moderate temperature. It seems possible that passive viewers which are sensitive to sufficiently long wavelengths can be developed (Cf. Chapter 1, Part II, and Chapter 6 of this report.) It is strongly recommended that fundamental research on detection which might lead to passive viewers be pursued.

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INFRARED GUIDANCE FOR SHORT RANGE AIR-TO-AIR MISSILES

R. Hofstadter, W. K. H. Panofsky and L. I. Schiff

Section I. GENERAL CONSIDERATIONS

1. Guided missiles can, in general, be classified into the following groups:

- (1) Command or programmed guidance
- (2) Beam rider
- (3) Active guidance (Illumination provided by missile)
- (4) Semi-active guidance (Illumination provided by attack plane)
- (5) Passive guidance (The target is the radiation source). The main use of IR in this problem is that it makes passive guidance possible since usual air targets radiate, reflect or obscure a sufficient amount of IR energy to permit detection above noise at ranges comparable to those of present air-to-air rockets.

2. The use of IR as a means of guidance results in certain desirable features of the guidance system. These are:

- a. Reasonable freedom from countermeasures
- b. Freedom from intercept
- c. After launching of the missile the parent aircraft has freedom of choice of tactics
- d. High angular resolution
- e. In general, the electronic and mechanical design is relatively simple. This is particularly desirable for easy maintenance.

These points will be discussed further in relation to the corresponding radar systems.

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3. The use of IR as a means of passive guidance imposes tactical limitations which have to be carefully evaluated in comparing it to other guidance systems. We will list those which apply in general to all IR systems now under consideration.

- a. IR seekers are inoperable in clouds, fog or rain in which the target is not visible to the eye.
- b. IR seekers become inoperable if the seeker axis makes an angle of less than 10° with the direction to the sun.
- c. A range signal is not available.
- d. IR missiles have certain limitations regarding their ability to discriminate against nonuniform backgrounds, which have been discussed in some detail in Chapter 1.
- e. A seeker has two characteristic angles: the "field of view angle" which defines the maximum initial angle between the seeker axis and the line of sight to the target which will permit the seeker to lock, and the maximum allowable angle between the seeker axis and the missile axis. The latter depends on mechanical design limitations; the former must necessarily be made small in an IR seeker to reduce the total amount of sky energy "seen" by the seeker. This imposes narrow tolerances on the accuracy of initial aim.

4. A detailed comparison of radar and IR systems has been made in Chapter 2 of this report. We shall only summarize the relevant points here.

- a. IR systems permit a high angular resolution as compared to radar systems in which the "dish" diameter must be small.
- b. IR requires even less electronics than "Range-only" radar. As a result, IR seeker systems are considerably cheaper, lighter and of lesser electronic complexity than radar seekers.
- c. IR seekers homing on active heat sources are less subject to large fluctuations in magnitude and direction of the signal when approaching a target than are radar seekers (glint).
- d. IR homers are probably less subject to countermeasures than radar seekers.

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- e. IR guidance systems do not require a significant amount of equipment in the "mother plane"; this is not important in all cases since certain future fighters will use air intercept radar which is also suitable to illuminate targets for semi-active radar homers.
- f. It should be pointed out that at the short ranges at present considered for air-to-air IR guidance, completely active radar systems are entirely practical; e.g., for an active system on X-band with 5" antenna, 2 to 3 watts average power would suffice for a range of 2 miles. Completely active radar and passive IR requires no additional equipment in the parent aircraft (see g below).
- g. It should be added to e and f that for use at night or under conditions of low visibility, search radar has to be carried with IR homers and radar active missiles.
- h. IR homing weapons as well as active radar systems require no tracking after launching. This is not true for semi-active or beam rider missiles.

Section II. IR GUIDANCE SIGNALS FOR AIR-TO-AIR WARFARE;
ATTAINABLE RANGES

In this section we shall consider the types and magnitudes of signals obtained from suitable military targets and, largely by way of examples, shall attempt to indicate the general reasoning by which signals and ranges are obtainable from theory.

A. The first and simplest type of signal is that obtainable from a hot body. We may call such a target a positive radiator. Examples of positive radiators are jet tail pipes, jet plumes, the sun, reciprocating engines and their exhaust stubs, etc. Countermeasure devices such as flares also belong to this category. A high speed missile which is heated by friction is another example of a positive radiator. The total amount of energy radiated per unit time does not provide a complete description of positive targets because the temperature of the source is an important parameter affecting the spectral distribution of emitted energy. The temperature of the source, therefore, determines the type of detector which can be used. A photodetector, for example the PbS photoconductive cell which has a long wavelength cutoff in the neighborhood of 3.0 microns, would be at a disadvantage where the temperature of the source is less than 250°C.

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In the case of positive targets it is possible to develop a completely passive seeker. At present the best military example of a suitable positive target for a passive homing seeker is a jet tail pipe observed at night in a clear sky. In daytime above the clouds the situation is almost as favorable, but when a jet appears against a cloud background illuminated by the sun it is clear that without proper precautions only a noise-invested, and therefore inadequate, signal would be available for a potential seeker. It is, therefore, necessary in discussing positive signals and signal strengths to consider the radiation from whatever background is present. This has been done in part in Chapter 1 and further details are presented in what follows.

B. A second type of signal is obtained by obscuration of a portion of a bright background. Such a signal may be called negative. In military work such signals previously have been recognized to be of value for proximity fuzes and have been called shadow or silhouette signals. Obviously the silhouette signal is obtainable only in daytime or near-daylight conditions. The strength of such signals can be roughly estimated, but it should be recognized that existing data on sky and cloud emission for various infrared wavelengths are not complete. Recently data observed at sea level have been reported by C. P. Butler (Naval Research Laboratory Report No. 3984, July, 1952).^{*} In the visible spectrum a reasonably good estimate is available.

C. A third type of signal may be obtained in daylight by reflection of sunlight from a portion of an aircraft or missile. Such signals will depend on the position of the sun relative to the aircraft and the seeker and on the presence or absence of clouds or haze in the sky. Even in favorable cases of sun illumination of the target the high speed of present-day aircraft may cause the aspect to be changed sufficiently during a single tracking run that the signal may develop from a positive reflected sunlight signal and go through zero to a negative silhouette signal. The positive sun signal will therefore frequently have a more or less accidental character. The reflected sun signals may also be important because, when large enough, they may temporarily desensitize and confuse a missile seeker.

D. A fourth type of signal results from modulation at acoustic frequencies of radiation from propeller-driven or jet aircraft. In the former case, propeller chopping of radiation from engines has been observed to give recognizable signals (Baird Associates work). Very little seems to be known about whether acoustic modulation of jet radiation exists. Because of the importance

^{*} A discussion of Butler's results is given in Volume II, Chapter 1, Part III, Part III, Chapter 1, also gives a general discussion of sky backgrounds.

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of such modulation in distinguishing jet targets from background it would seem worthwhile to perform experiments to decide the point.

A-1. Positive Targets

The amount of radiation from a jet tail pipe, or exhaust stub of a reciprocating engine, through the atmospheric windows is known to be of the order of one kilowatt in the spectral response region of the PbS cell (0.3 - 3.0 microns).^(1,2) This empirical figure checks reasonably well with the following calculation based on known temperature conditions⁽¹⁾ in the interior of the tail pipe (~700°C.) or exhaust stubs. Using the Stefan-Boltzmann law, the emitted power is given by the expression

$$E = 5.72 \times 10^{-12} T^4 \text{ watt/cm.}^2 \quad (1)$$

With a Kelvin temperature of 973°K. and a tail pipe with a diameter of two feet one obtains 14 kilowatts for the total amount of heat radiation proceeding from the entire tail pipe. Assuming an emissivity of about 0.5, one obtains an actual radiation yield of 7 kilowatts. This radiation lies in the spectral region beyond 1.0 micron and has a peak near 3.0 microns. The PbS detector has appreciable sensitivity only at wavelengths less than three microns. For the purposes of a rough calculation we may consider the PbS sensitivity as constant over the three relevant windows of the atmosphere (1.18 - 1.33, 1.52 - 1.75, 2.00 - 2.31 microns). We may make a numerical integration within the windows and over the black body radiation curve for 973°K. and find that 8 per cent of the total energy emitted lies in the useful region of the PbS characteristic. (In this connection, Ovrebo⁽²⁾ gives an empirical figure of 10 to 20 per cent for the radiation transmitted over small distances. Over small distances we may expect incomplete absorption by water vapor while our calculated figure refers to complete absorption.)

Hence we find that 8 per cent of 7 kilowatts, or 0.56 kilowatt, will be radiated in the PbS region. The order of magnitude agreement between the calculated and empirical figures shows that no significant factor has been overlooked and that the simple theory presented here may be used with some degree of confidence. Verification of the calculated results of this section may also be found in the complete analysis by W. W. Kellogg.⁽³⁾

(Some further remarks concerning water vapor absorption are pertinent at this point. The water vapor content at high altitudes diminishes rapidly as the altitude is increased. At 40,000 feet the amount of water vapor is essentially zero. Hence the correction for absorption of infrared radiation in the PbS region by water vapor should not be included in high altitude considerations. In this case the percentage of black body radiation in the PbS region at 973°K. is 21 per

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cent instead of the 8 per cent including absorption effects, and the ranges calculated below are then expected to be 60 per cent larger than those allowing for complete absorption by water vapor. The effect of CO₂ in the atmosphere is small in the PbS region.)

The angular distribution of radiated energy is not uniform. Diagrams of typical radiation patterns for jet aircraft are given in Chapter 1 (Figures 4,5). In the case of a cosine square pattern in the rear hemisphere the power emitted per steradian in the back direction (along the axis of the tail pipe) is $3/2\pi$ times the total power, thus 270 watts per steradian. The power emitted in the forward direction is very small. Measurements have also been made on B-29 engines by British⁽¹⁾ investigators, who find that a uniform pattern in the rear hemisphere is obtained with exhaust stubs at 700°C. internal temperature at the center of the hemispherical pattern. In this case the emitted power in the backward direction is $1/\pi$ times the total power or 180 watts per steradian. These figures are confirmed by actual observations on propeller-driven and jet aircraft.^(1,2)

For general usage we shall take a mean figure of 200 watts per steradian in the back direction in the PbS region for a single jet engine or a single large reciprocating engine. Because of the greater sensitivity of PbSe at longer wavelengths PbSe (at 23°C.), in place of PbS, would give the corresponding figure of 400 watts per steradian, and this would represent 16 per cent of the total radiation. Complete absorption in the water vapor bands is assumed. About 21 per cent of the total radiation, or 570 watts per steradian might be obtained using presently known PbTe detectors. In order for these figures to hold it must be assumed that the same absolute sensitivity would have to be obtained in PbSe and PbTe as now found in PbS under comparable conditions of cell size and amplifier band-width. At low temperatures the behavior of PbTe seems to satisfy these conditions. Other desirable properties of the long-wave detectors may make PbSe and PbTe desirable even though the gain in detectable energy is only a little more than a factor of two. For example, the ability to observe lower temperature targets is extremely important.

If we assume conventional optics for a missile seeker and neglect atmospheric absorption of infrared radiation in the atmospheric windows, we may estimate the range of detection when it is limited only by detector noise. Let us take an example to clarify the ideas.

The three-inch diameter mirror will collect at range 10 miles an amount of energy per unit time given by the inverse square law:

$$S = 200 \frac{\text{watts}}{\text{steradian}} \times \frac{\pi}{4} \left(\frac{3}{12 \times 5.28 \times 10^4} \right)^2 \text{ ster} = 3.3 \times 10^{-9} \text{ watt}$$

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for tail aspect. The noise in uncooled Eastman PbS cells appears to be equivalent to a received power at about 2 microns of 4.0×10^{-13} watts per square millimeter of cell area and for unit cycle per second band-width. A representative homing seeker with a scanning system corresponding to a three-inch mirror may employ a band width of 100 c.p.s. and cell area of 25 mm.²* Hence, a typical cell noise figure will be 1.0×10^{-9} watt. The signal S given above will appear as an amplitude modulation over the background illumination, and we shall assume that the whole signal is effective. Hence, if no absorption occurs in the atmospheric windows and cloud background gradients are ignored, the signal observed from a jet tail pipe may be as large as 3.3 times the detector noise power at a range of ten miles.

Assuming a $\frac{\sqrt{3}}{1}$ ratio in voltage⁽⁴⁾ (not power) between minimum detectable signal and cell noise, one notes that a range of ten miles should be obtainable. The assumptions made above are quite likely to hold in the absence of fog, bad sky gradients or clouds. On a clear night the conditions are nearly perfect and a ten-mile range is to be expected.

The diameter of the mirror and the f-ratio (which for the same mirror diameter affects the required cell size) may be improved to give larger ranges. Ovrebo⁽⁴⁾ using a 10-inch aperture has already reported ranges of the order of 20-60 miles. Large bombers would, therefore, be detectable at ranges exceeding twenty miles in good weather at night.

It appears that fighters and other jet aircraft of the future will make large use of afterburners, especially under conditions of combat maneuver. The "fireball" trailing behind an aircraft actively using an afterburner will provide a much larger positive signal than any jet tail-pipe signals we have so far considered. According to engineers of Douglas Aircraft Co., present-day afterburners emit a fireball, entirely outside of the aircraft, averaging perhaps 800-900 sq. in. area and having a length perhaps six to fifteen feet long. The average temperature of such a fireball is in the neighborhood of 1900° Kelvin. Such a source would emit an omni-directional radiation pattern with radiant intensities perhaps 30 to 100 times as much as that proceeding from the rear of a jet's tail pipe. The radiation spectrum will have a peak near 1.5 microns, and a considerable amount of the energy will lie in the visible spectrum. The effects upon signal strength, range, background discrimination, etc., are important for such intense sources

* Equivalent noise power input will be proportional to the width of the frequency band employed.

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and make the problem of the seeker very much easier under combat conditions. The likelihood of developing a countermeasure for such sources seems remote. The only effective countermeasure would seem to be to leave the afterburner turned off whenever possible, which of course is also desirable from the viewpoint of conserving fuel.

The figure of 100 c.p.s. (band width) used above was chosen for a case when high tracking accuracy is needed, as for example, in a homing missile. This comes about as follows: Let $10^\circ/\text{sec.}$ be taken as an example of maximum angular tracking speed desired and 0.1° as the angular tracking accuracy required. The seeker system must then receive intelligence in no more than 0.01 second. This means that the normal band width of the amplifier must be of the order of 100 c.p.s. or higher. If we are interested in a slower search or reconnaissance instrument the band width may be reduced to perhaps 10 c.p.s. and the noise will become 1×10^{-10} watt. In this case, for the same minimum detectable signal to noise ratio (voltage) of $\sqrt{3}$, the range will be thirty miles. As stated above, the search equipment AN/AAS-1 (XA-1) has tracked targets as far as 20-60 miles.

B-1. Silhouette Targets

In calculating the silhouette signal we assume that a certain typical target area, e.g., about ten square meters for a medium jet aircraft, will completely obscure the background sky light. The simplest calculation can be made for a detector of the PbS variety which is sensitive to the visible region of the spectrum as well as a portion of the infrared. The sky background* is due to the scattered light of the sun and the blue color is well known to be the result of statistical density fluctuations of the air. The explanation of the properties of sky light is due to Rayleigh (1899) and assumes that the air is free of dust; in other words, that particles larger than the prevalent wavelengths in the sun's spectrum are not present. Under these conditions and the absence of absorption, the scattering cross section can be shown to be inversely proportional to the fourth power of the wavelength of the scattered light. The black body curve for the sun ($6,000^\circ\text{K.}$) shows that radiant energy falls off very rapidly in the ultraviolet below 0.3 micron. Furthermore, the absorption due to atmospheric ozone is intense in this region. Hence, the spectrum of scattered light shows a maximum in the neighborhood of 0.4 micron, i.e., in the blue. Figure 1 shows a spectral analysis⁽⁵⁾ of the daytime sky intensity.

* The sky background is discussed in detail in Chapter 1, Part III.

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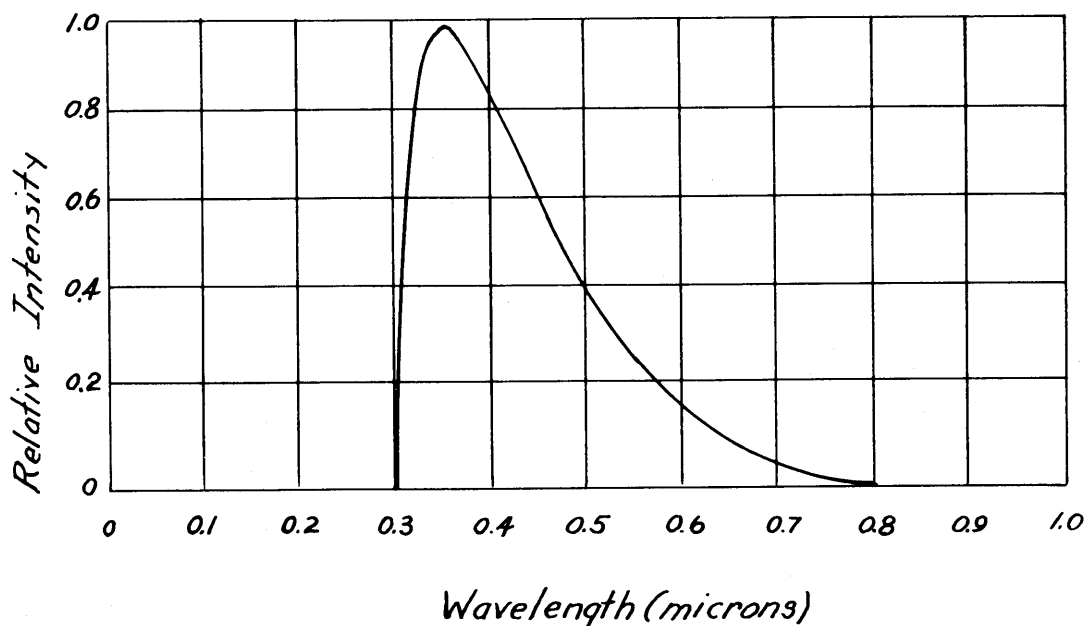


Figure 1 - Spectral Intensity of the Daytime Sky

The long wavelength tail of the scattering curve falls off rapidly because of the λ^{-4} scattering relation as well as the decrease in the black body curve for the sun at longer wavelengths. The black body curve:⁽⁶⁾

$$E(\lambda)d\lambda = \frac{hc^2}{\lambda^5} \frac{1}{\left(e^{\frac{hc}{\lambda kT}} - 1\right)} \frac{\text{ergs}}{\text{sec. cm.}^2} d\lambda \quad (2)$$

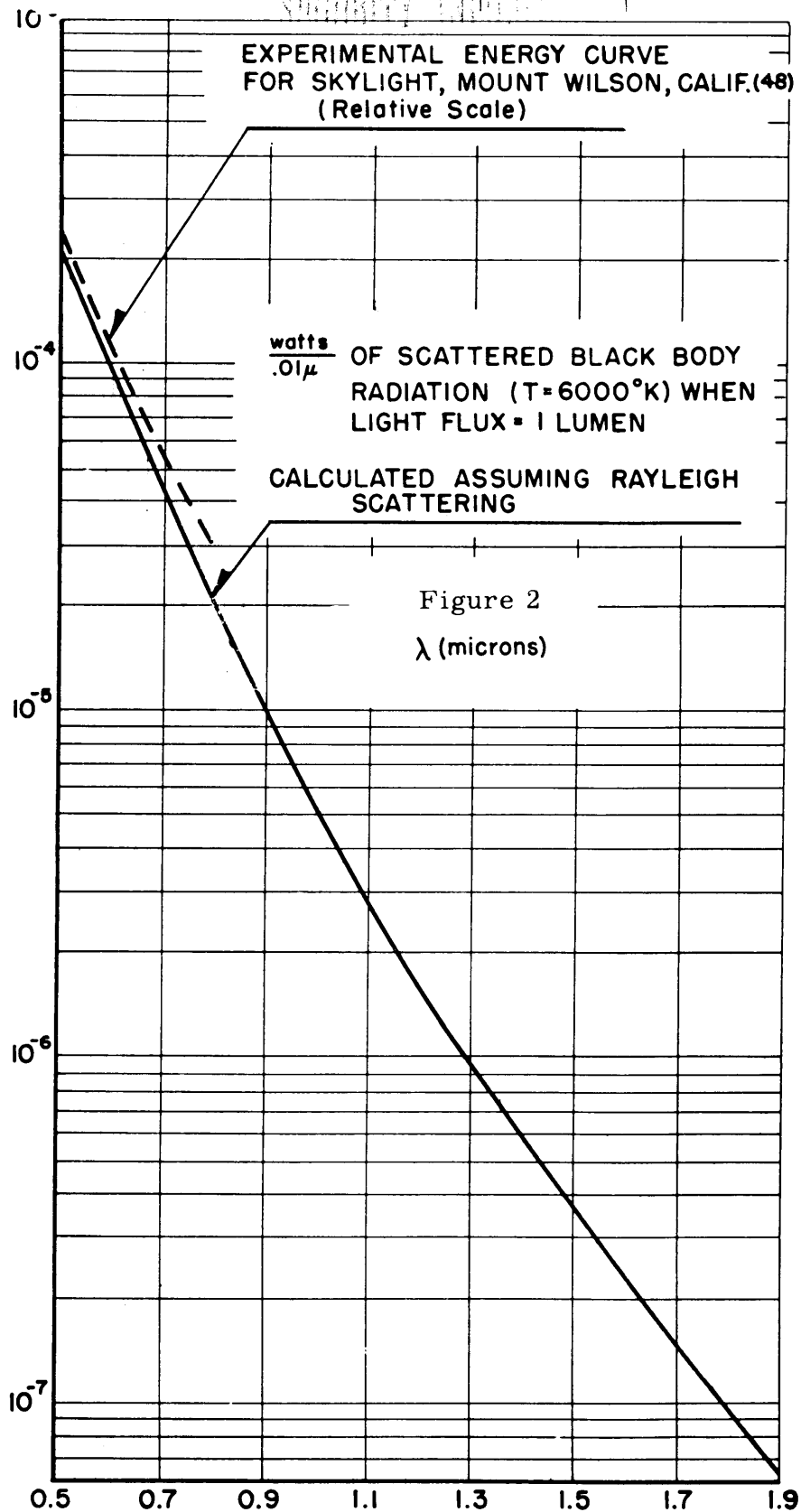
falls off approximately as λ^{-4} at long wavelengths. Hence, the sky light curve of Figure 1 will fall off as $d\lambda/\lambda^8$. The exact result is

$$\frac{Q}{w} = \frac{5.4 \times 10^{-5} L}{\lambda^9 \left(e^{\frac{2.4}{\lambda}} - 1\right)} \quad (3)$$

where L is a visual measure of sky brightness in lumens per cm.^2 , w the solid angle viewed and λ is given in microns. Q is the energy in watts/cm.^2 per hundredth micron wavelength interval. For typical conditions in clear weather L has a value about unity. Experimental results are given in Garrison's report⁽⁶⁾ in the form of a curve reproduced in Figure 2. A theoretical curve corresponding to equation (3) is also given in the figure and has been used in extrapolation of existing results, neglecting absorption and multiple scattering. A detailed discussion of these and other sky background characteristics is given in Volume II, Chapter 1, Part III.

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From equation (3) or from Figure 2 we may find the total amount of radiation in the PbS region by integration of the curve beyond any short wavelength cutoff, obtained for example by means of a filter. The filter is considered at this point because many IR seeker systems avoid unused and, therefore, unnecessary sky background by eliminating certain portions of the visible sky illumination.* Unused light energy may produce cell saturation which causes loss of signal (see Paragraph B-2 of this report). At the same time, of course, the silhouette signal is reduced by the filter by an easily calculable amount.

By obscuring with a target a certain amount of sky in the useful spectral range, we obtain a silhouette signal as follows. Consider the total energy contained between 0.5 micron and 2.0 microns, which by integration over the curve of Figure 2, amounts to 2.7×10^{-3} watt/cm.² per steradian. Absorption of light by water vapor is neglected in this calculation and makes very little difference when included. With a ten-square-meter target at ten miles the signal observed will correspond to the energy found in the appropriate solid angle:

$$w = \frac{10 \times 10^4 \text{ cm.}^2}{(1.6 \times 10^6 \text{ cm.})^2} = 4 \times 10^{-8} \text{ steradian.} \quad (4)$$

For a receptor area of one cm.² approximately 10^{-10} watt is observed by the target. If the mirror diameter is three inches the signal corresponds to 4.4×10^{-9} watt. For simplicity we assume an average uniform sensitivity of the PbS cell in the IR regions considered. When the filter cutoff is 0.75 micron (0.75 - 2.0 micron range) the energy becomes 5.4×10^{-4} watt/cm.² per steradian and hence the signal is 7.4×10^{-10} watt/cm.² for the three-inch mirror. For a 1.0 micron filter cutoff the corresponding figure is 1.4×10^{-10} watt. Hence, the silhouette signal is lost rapidly as the cutoff wavelength is increased. If no filter at all is used (assuming the PbS characteristic to be essentially flat from 0.3μ to 2.0μ) the maximum obtainable signal at ten miles is approximately 1.7×10^{-8} watt as determined by inclusion of the range 0.3μ to 0.5μ given in Figure 1.

The calculation therefore shows that the negative silhouette signal (4.4×10^{-9} watt at ten miles) is approximately equal to the positive jet tail-pipe signal (3.3×10^{-9} watt at ten miles) when the range of wavelengths used lies between 0.5 micron and 2.0 microns. The inclusion of longer wavelengths makes no improvement in the silhouette effect when the lower cutoff lies at 0.5 micron. As the lower cutoff moves toward the infrared, the silhouette signal rapidly becomes smaller than the jet signal. These results are independent of range.

In the case of an air-to-air missile the observed silhouette signal may vary because the target will be seen, not necessarily from below against a clear bright sky, but perhaps against the horizon or even from above, against earth,

* Volume II, Chapter 1, Part IV.

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sea or clouds. Moreover, the position of the sun in the sky can be important, particularly as the target nears the sun.

A consideration of all possible cases is beyond the scope of the present treatment. However, the effect of viewing targets against different portions of the sky is not likely to change the silhouette signal by more than about a factor four, except under the specific conditions that the target is on the horizon or very near the sun or when the sun is near the horizon. Other special conditions may occur when the target is seen from above, against clouds, in which case the brightness is increased by about a factor two.⁽⁵⁾ In viewing targets through thin cirrus clouds, the increase in brightness may be as much as a factor five or six.

The factor four, mentioned above, can be justified by the observation that sky brightness B , measured by a PbS cell, may be represented by the partly empirical formula:⁽⁵⁾

$$B = B_0 \sec. Z (1 + \cos.^2 \gamma), \quad (5)$$

where γ is the angle between the sun and the direction of observation in the sky, and Z is the zenith angle, that is, the angle between the direction of observation and the zenith*. If target viewing is restricted to the range $0 < Z < 60^\circ$ and γ is unrestricted (we exclude $\gamma = 0$ for this means facing the sun) one obtains a maximum value of $4B_0$ and a minimum value of B_0 . The range covered thus includes a large fraction of the total solid angle of the sky.

There is a reduction in sky background at increased altitudes because there one encounters less and less air to scatter the entering sunlight. For example,⁽⁵⁾ at solar zenith angle $\psi = 55^\circ$ and $\gamma = 55^\circ$ the sky brightness decreases typically from about 1.6 in arbitrary units to 1.2 at 10,000 feet altitude, 0.8 at 20,000 feet, and 0.6 at 30,000 feet. Data taken by Hughes Aircraft Company engineers give 0.23 in the same units at about 50,000 feet. Hence, operating at 20,000 feet one has about half the sky intensity observed at sea level. For high altitudes the range figures given earlier for the silhouette effect must be reduced by the square root of the factor in light reduction, for example, by a factor of 1.4 at 20,000 feet. Above clouds the reduction in range may not be observed and in fact the effective range may even be increased by a factor of about 1.4.

Figure 3 shows a summary of sky brightness data⁽⁵⁾ in arbitrary units for various zenith angles, scattering angles, etc.

B-2. Cancellation and Saturation Effects

At night a positive target may be observed against essentially zero background. It may also be possible under daytime conditions to employ a filter such

* Further details on sky background are given in Volume II, Chapter 1, Part III.

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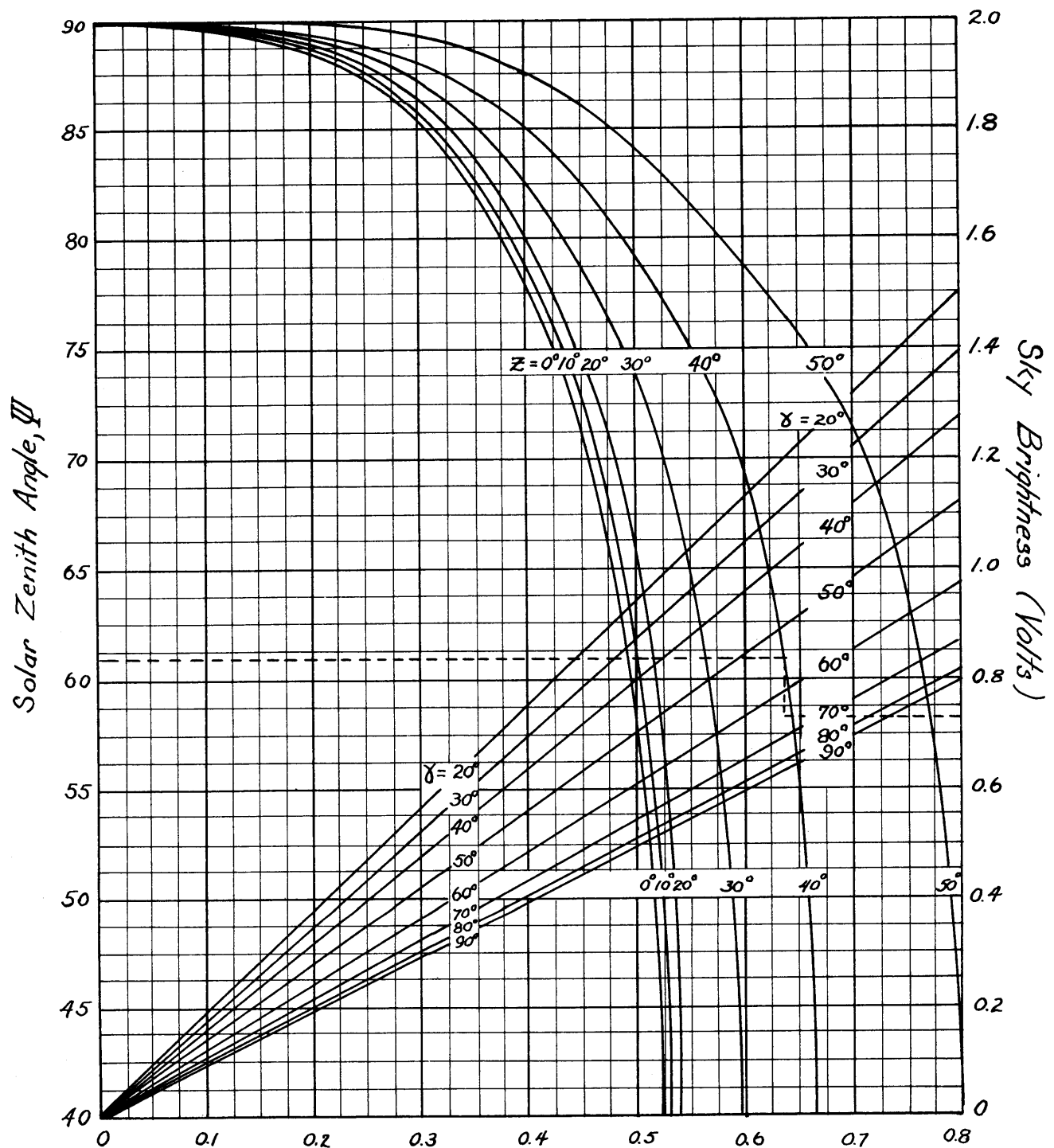


Figure 3

Sky brightness diagram. Parameters are solar zenith angle, Ψ , zenith angle of observation, z , and scattering angle (arc between point observed and sun), γ . To obtain brightness find point of intersection of Ψ and z , move vertically from this intersection to the proper value of γ , from this point move horizontally to the right and read the brightness.

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that some cloud and sky backgrounds are removed, while at the same time permitting jet target radiation to be transmitted. In this connection detectors like PbTe, which are sensitive beyond 2.7 microns, would make filters more valuable. However, in the general case, a hot target will appear on top of a hot background and must be distinguished from it. It is thus evident that if the visible component of sky background, as well as cloud background, is not filtered out, it is possible for the positive hot exhaust and negative silhouette signals to cancel each other. This circumstance may well be relatively uncommon but nevertheless may occur when the seeker detects and averages positive and silhouette signals. The reflected sun signal and the silhouette signal may also cancel as discussed in C, below.

When a filter is not used for removal of the visible spectrum, the large amount of background energy available may saturate the PbS cell. Hughes' data* show that an input of 10^{-4} watt into a 4-mm.² cell produces a 30 per cent drop in sensitivity. For a 4° total cone angle of view the total energy in the visible and infrared PbS region collected by a three-inch mirror would be about 10^{-3} watt. With a three-inch mirror one might use a 25-mm.² PbS cell and therefore the cell, subject to these conditions, would be saturated by about the amount in the Hughes case. This is one argument used in favor of a filter.

Scanning and target seeking have also been performed with the silhouette effect and an RCA 5819 photomultiplier which peaks in the green portion of the visible spectrum. The contrast between clouds and sky is not nearly as great in this region as in the infrared. This work has been carried out very recently by Baird Associates, Inc. Although considerable success in tracking has been attained, it has been reported by Metcalf observers that very sharp cloud edges sometimes deceived the seeker in this case but rather less than in the case of an infrared detector. The Baird scanning has been aided by a small field of view ($\frac{1}{2}^\circ$) which may be rather undesirable in homing seekers. For slow search, this system could be quite suitable, although, of course, of no use at night.

C-1. Effect of Reflected Sunlight

The signals to be expected from reflected sunlight may arise in at least two ways. Estimates of these signals will be carried out in the following paragraphs.

Case (1): A plane portion of the aircraft reflects sunlight directly into the aperture of the seeker. In this case the light comes essentially directly from that fraction of the sun's surface subtended at the seeker by the aircraft surface,

* Personal communication from W. Craven.

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except for the loss due to metallic reflection. Numerically this means that at a range of half a mile and reflecting area of 1.0 square meter approximately 1/50 of the sun's surface is effective. For shiny aircraft, the reflection coefficient lies between 0.5 and unity, while for painted aircraft perhaps 0.1 or 0.05 might be typical figures. If a representative value of 0.5 is used, the radiant power arriving at the seeker collector mirror will be 0.00168 watt/cm.², and almost all this energy will be in the PbS region. This figure is obtained from the reflection coefficient (0.5) and direct measurement of the sun's intensity at the surface of the earth (0.129 watt/cm.²). At a range of half a mile a three-inch diameter mirror collects about 0.07 watt and directs all of this to the PbS cell. The cell will be completely saturated and may take a few seconds to recover.* The amplifier circuits may also saturate and require a small interval of time to recover. In either case the seeker will probably be confused and lose the target. The possibility of obtaining a directly reflected sunbeam in the receiver is probably small but should be evaluated.

The possibility of obtaining directly reflected signals is certainly smaller than the second type of signal to be discussed below, and therefore, will be neglected from the point of view of providing a tracking signal. On the other hand, once in a great while a directly reflected sun signal may be discerned by a seeker at an extremely large range.

Case (2): There is no really flat mirror-smooth surface on the aircraft, but there are shiny rounded or painted portions of the order of 1 square meter in area which act as diffuse sources. We may assume that these areas act as new sources, emitting radiation according to the inverse square law. At 10 miles and for a reflection coefficient of 0.5, an area of one square meter of diffuser sends to the three-inch receiver a signal of

$$\frac{10^4 \text{ cm.}^2 \times 0.068 \text{ watt/cm.}^2 \times 44 \text{ cm.}^2}{(1.6 \times 10^6 \text{ cm.})^2} = 1.19 \times 10^{-8} \text{ watt.}$$

In this case the figure 0.068 watt/cm.² results from assuming the whole area of the sun to be effective, which is reasonable for a diffuse reflecting source. By comparison with the jet tail-pipe signal, $S = 3.3 \times 10^{-9}$ watt, at ten miles it may be seen that the sun-signal is quite appreciable whenever a favorable aspect of aircraft-sun-seeker obtains. Just what fraction of the time such signals may be expected is difficult to estimate but deserves attention. Empirically, Inyokern engineers have asserted that sun-signals are definitely obtainable at certain times and have taken tracking photographs showing such conditions. Cancellation of sun and silhouette signals would seem to be a not improbable situation, at least at certain aspects.

* According to A. J. Cussen of NBS Corona, 0.1 watt/mm.² produces changes of sensitivity and time lags in PbS cells.

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At short ranges a similar calculation shows that, e.g., at 100-250 ft. the radiant energy from a diffusely reflected sun-signal is enough to saturate a PbS cell. It is not clear that in this case the target would be lost even though the seeker might become confused. At some time it may be desirable to conduct simple simulated experiments in the laboratory to provide information on this point.

Section III. TACTICAL CONSIDERATIONS REGARDING IR GUIDED MISSILES

A. General

1. At this writing (October 1, 1952) the only air-to-air missile which has been test fired is the Sidewinder and in that case only two preliminary firings have been made. It is, therefore, a matter of importance to make available guided missiles in quantities sufficient for tactical tests, even if such missiles do not represent optimum performance. It is at least feasible that IR air-to-air missiles will provide this opportunity and do it cheaply. In addition, we believe that the air-to-air IR guided missile program will provide the first test of the role IR can play when applied to a major weapon.

2. In order to aid understanding of the tactical problems, a meeting was held at CNO on 29 and 30 January, 1952. The following operational personnel were requested to make statements regarding the potential use of an IR guided short-range missile (ranges up to 4 miles were quoted to them) in their operations:

- (1) Col. G. T. Eagleston, CO 4th Fighter Group; F-86, USAF;
- (2) Captain Cameron Briggs (USN, NA; CO USS BOXER);
- (3) Lt. Walter M. Schirra, Jr. (USN; 90 missions with 136th Fighter Group)

The results of this interview are given under Sections 3 to 6. These answers should be taken with due caution since they are based only on gunnery experience.

3. In combat involving essentially equally matched fighters (such as the MIG-15 and F-86), the greater range of a missile (say 10,000 feet) may well be a major advantage over the present effective range (estimated at 1,200 feet) of the .50 cal. guns of the F-86. Ranges in excess of 2 miles would not be useful in this case, since identification is at present too difficult in Korea. The required initial lock-on accuracy (approximately 17 mils) is not considered difficult since 2 to 3 mil accuracy is required in ordinary gunnery.

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4. One question on which a satisfactory answer is not available at this time is the tactical significance of limiting a chase to a tail cone. This limitation is due to the following sources:

- a. The radiation from jets is principally in the backward direction, while radiation from propeller-driven craft is essentially isotropic. If, however, homing proceeds via "the silhouette effect" the radiation pattern does not limit the angle of approach. Hence, this limitation depends upon the type of homing considered.
- b. The mechanical design of present American seeker heads limits the deviation between missile axis and seeker axis to angles of the order of 20° . In proportional navigation, this limits the approach angle to a tail cone of the order of $\pm 60^{\circ}$.
- c. Since precise tracking to within approximately 1° is required at launching to obtain lock-on, difficulties may be encountered at large angles of approach in the back hemisphere due to high angular rates of change of the sight line.

The relative importance of these items depends on the specific missile considered.

5. The possibility of erratic behavior of the missile because of clouds will, of course, affect both the offensive and defensive tactics. At high altitudes this will be fairly unimportant; also the progress in reducing cloud effects by filtration (Section V) will make this limitation less significant in the near future. The operational pilots questioned were not too seriously concerned about this question for high altitude fighter to fighter work.

6. There is a real question whether in high speed fighter to fighter combat, the loss in speed due to drag of the launching rails and the missiles will offset the gain in firing range attained by use of the missile. No accurate figures on launcher drag were available for very high speeds*. Presumably in the future, the rocket armament will be considered in the design of the aircraft.

* Data for F40-5N

<u>Altitude</u>	<u>Speed without Rockets</u> <u>(Knots)</u>	<u>Speed with 8 Rounds</u> <u>of HVAR (Knots)</u>
0	291	269
31,000	384	336

With two rockets mounted on the ends of the wings of a Meteor aircraft, the British have found little change in top speed. This seems to be a rather special compensation between increased drag of the rockets and improvement of the wing-end characteristics.

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7. The possible loss in speed due to the presence of the launchers is of relatively little consequence in fighter to bomber attack; in fact, a major usefulness of IR air-to-air guidance may lie in this field.

8. We are told that the U. S. Air Force is using unguided rockets in air-to-air firing directed by initial fire control. Clearly, the increase in the accuracy of rockets provided by guidance is an improvement over initial fire control.

B. Caliber of Missile

The proper missile caliber and warhead size for an IR air-to-air guided missile have been considered, but at present not enough information is available to make definite statements on this point.

Before any further decisions on the installation of IR guidance in a specific missile are made, it is recommended that the entire weapon be analyzed as to the suitability of IR guidance for that particular missile.

The factors involved here are as follows:

1. The reliable range of the IR seekers developed (and under development) at present is less than the range of the larger air-to-air missiles.

2. In general, one would like to maximize the overall performance of the armament of the firing aircraft. This involves a large number of complex factors, some of which are not known to date. It is therefore not surprising that the conclusions drawn by the different design groups as to caliber and weight are not in agreement.

The principal factors are:

- a. A small warhead (a few pounds) is lethal for a direct hit but nearly useless for a near miss.
- b. Charges of the order of 50 lbs. are dangerous up to miss distances of approximately 30' if proximity fuzing is used.
- c. A larger weight decreases the velocity and range and diminishes the maximum rate of turn. It thus decreases the hit probability.
- d. A given aircraft can carry more missiles if the weight is less.

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A quantitative "optimization" with these factors in mind is only possible in a rudimentary way since to date no experimental miss distance distributions exist and also since some of the material bearing on damage of explosives to aircraft is controversial.

Some studies* tend to indicate that a small missile with small warhead and contact fuze represents the best overall design. "Falcon" is based on this principle. On the other hand, the system believed optimum by the "Blue Jay" (De Havilland) engineers incorporates a heavier (45-lb.) head and proximity fuzing.

Even if a given missile can carry a heavy warhead, this does not necessarily mean that the largest load should be carried; e.g., "Sidewinder" (NOTS) can carry ~ a 45-lb. warhead which is about 30 per cent of its weight. Reducing this to ~10 lbs. will substantially increase the performance of the missile as to range and rate of turn; better damage probability might result.

Section IV. SCANNING SYSTEMS AND COLOR FILTERS

In Chapter 1, a general discussion of the scanning and filtering problems in terms of the target and background characteristics was presented. In the present section, a particular type of scanner will be considered in more detail; this has been incorporated in the first models of the Sidewinder missile, and similar scanners have been used in connection with the Falcon and Blue Jay (British) missiles and the Baird star-tracker.

1. Description of the Scanner

An image of the target background is formed on a rapidly rotating circular reticle. Immediately behind the reticle is placed a field lens which forms a much-reduced image of the objective optic on a PbS cell; this has the effect of spreading the radiation that passes through each portion of the reticle uniformly over the illuminated area of the cell, and thus greatly reduces noise due to non-uniform sensitivity of the cell.

The reticle consists of a number of sectors of varying transparency, formed by lines radiating from the center. A typical arrangement of these sectors has half of the field of 50% transparency, and the other half divided into $n/2$ opaque sectors alternating with $n/2$ transparent sectors, all of equal angular width. (Such a reticle with $n = 12$ is shown in Figure 4.)

* E.g., Bandels, Meeting of Sidewinder of 5-5-52 (NOTS).

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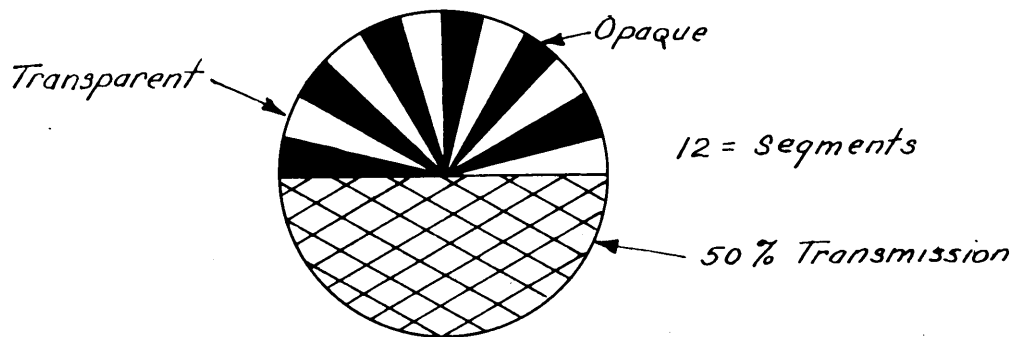


Figure 4

It can be shown* that if an off-center point source is viewed through a rotating reticle of this type, and a harmonic analysis is made of the output signal, the n th harmonic of the reticle rotation frequency is much stronger than any of the others.

It can also be shown* that if the intensity over the field of view can be written as a sum of products of powers of the rectangular coordinates x and y of the field, such that m is the largest sum of the exponents of x and y in each term, then no harmonics of the rotation frequency higher than m are present in the output signal. (For example, if $m = 1$, this means that the intensity in the field can be written as $A + Bx + Cy$, where A , B , and C are constants, so that the field is characterized by a uniform gradient of intensity. Then no frequencies higher than the rotation frequency itself are present in the cell output.) Now if the reticle has the form described in the last paragraph, the low harmonics of the rotation frequency are suppressed with respect to the n th harmonic, so that if n is somewhat larger than the number m that characterizes the background, the background signal is substantially reduced.

The discussion of the last two paragraphs can be considered qualitatively as follows: Each half of the field of view is "looked at" alternately by the 50% transmitting half of the reticle and by the sectored half. If these two halves of the field have different average intensities, no signal results because of this difference, since the two halves of the reticle transmit equally. This is the property from which the background discrimination arises. If on the other hand a small target is also present in the field, a higher frequency signal is obtained from the sectors, and this signal is interrupted once every rotation of the reticle by the passage of the 50% semicircle. Thus not only does a reticle of this type discriminate against background in favor of small targets, but it also senses the

* Some of these points are discussed by T. R. Whitney and L. W. Nichols in NOTS TM 345 (January 3, 1952).

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direction in which the target image is displaced from the center of the reticle. This last piece of information is obtained from the phase of the interrupted portion of the target signal. Alternatively, the target signal can be Fourier-analyzed into a main frequency (equal to n times the reticle rotation frequency) and side bands (separated from the main frequency by small multiples of the rotation frequency) which together give the necessary phase information.

Further suppression of the background can be achieved by passing the cell output signal through electrical filters that pass only frequencies in the neighborhood of n times the reticle rotation frequency. However, if the background has very strong gradients, the low harmonics may be relatively strong even after suppression by the reticle, and thus make a heavy demand on the electrical filter design. This burden can be lightened by modifying the reticle sector angles so that nothing is passed in the low harmonics. A recent reticle design suggested by T. Whitney at NOTS Inyokern makes the transmission of the reticle proportional to $(1 + \sin \theta) \sin n\theta$, where θ is the polar angle with respect to an axis fixed in the reticle. While more difficult to fabricate, such a reticle would transmit only the n , $n - 1$ and $n + 1$ harmonics of the rotation frequency; this combination suffices to provide the sensing information needed to guide the seeker into a target that is off center.

2. Checkerboard Modification

A perfectly sharp cloud edge that crosses the field of view will give a background signal that contains high harmonics of relatively large strength, and thus cannot be distinguished from a target. The attempt is now being made to suppress such edge (background) signals with respect to point (target) signals by changing the scanner to a checkerboard pattern (see Figure 5).

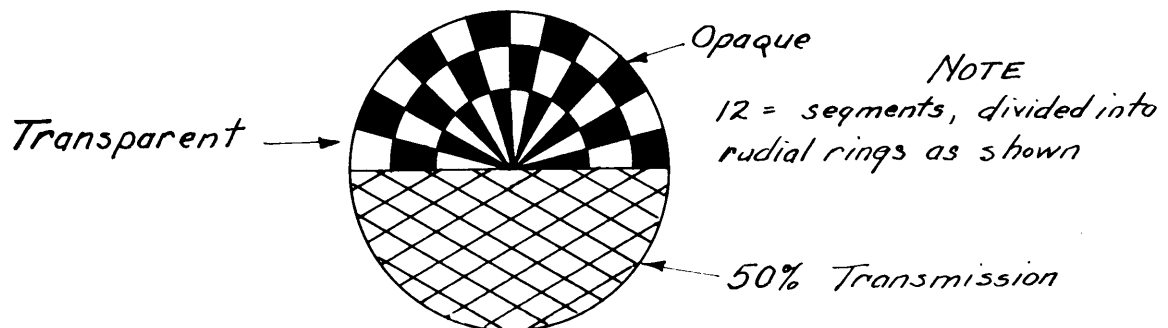


Figure 5

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It is easily seen that the harmonic analysis of the output signal arising from a point source is the same for the sector and checkerboard reticles of Figures 3 and 4, respectively. Further, it seems plausible that the output signal arising from an edge source will be substantially less for the checkerboard than for the sector reticle, because cancellation of the radiation from different parts of the edge will be more pronounced in the former case.

A preliminary theoretical analysis of this situation has recently been made at Stanford University, and indicates that the signal power arising from a sharp edge is reduced by a factor of about 10 when the reticle is changed from sector to checkerboard type. Further study of this point would be well worth while, perhaps as a special case under item (b) of page 69. An empirical trial at TRE in England with a somewhat different scanner is in agreement with the above-mentioned calculation. This trial was made with a seeker in which the reticle is fixed and the image of the field of view is moved in a circular path (conical scan) over the reticle. The performance of such a scanning system is compared qualitatively with that of the rotating reticle scanner in Section 4.

The checkerboard modification can also be introduced into the $(1 + \sin \theta) \sin n \theta$ reticle and others of this type, by dividing the reticle pattern into radial rings, and displacing successive rings by an angle π/n with respect to each other.

3. Use of Color Filters

A single color filter can easily be attached to a scanner of this type, simply by placing it at a convenient point in the optical path. The results expected from such a change are discussed in Section 5, Part IV, Chapter 1.

In similar fashion, two balanced color filters of the type discussed in Section 6, Part IV, Chapter 1 can be used in place of the opaque and transparent sectors considered in the two preceding sections. The 50% transmitting semi-circle would then have to be replaced by either of the filters with transmission reduced to half.

Balanced color filters would be more difficult to apply to the $(1 + \sin \theta) \sin n \theta$ reticle. However, complete suppression of an arbitrary number of low harmonics can in principle also be achieved by using alternating opaque and transparent sectors of appropriate (unequal) angular widths. These sectors can then be replaced by color filters, as discussed in the preceding paragraph.

4. Other Types of Scanners

Other kinds of scanning systems are, of course, possible. A particular type developed for the Hughes star-tracker consists of a rotating reticle that has

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n opaque and n transparent sectors, all equal, extending in symmetrical fashion completely around the circle. Such a reticle passes only background signals of frequency $n, 2n, 3n, \dots$ times the reticle rotation frequency, and so would completely suppress backgrounds for which the number m of Section I is less than n . Because of its symmetry, however, this reticle would provide no target direction sensing information.

This defect is remedied by nutating the image of the field of view around the center of the reticle at a frequency much less than the reticle rotation frequency (conical scan). The background then introduces low harmonics of the nutation frequency, which must be removed by electrical filtering. The filtering job is simplified by choosing a large ratio between reticle and nutation frequencies. The main target signal frequency (n times the reticle rotation frequency) is then amplitude or frequency modulated or both at the nutation frequency, depending on the size of the target image and the ratio of the radius of the nutation circle to the radius of the reticle. This modulation, which may also be expressed in terms of sidebands of the main target signal frequency spaced apart from it by multiples of the nutation frequency, provides the necessary directional sensing information.

Another type of scanning system, considered in connection with Blue Jay, the British IR homing missile, was mentioned in Section II. In this scheme a stationary reticle like that illustrated in Figure 4 or Figure 5 is placed in the image plane, and the image field is nutated around the center of the reticle. The principal target signal frequency is then n times the nutation frequency. There will be background signals arising from variations in the background intensity over the field of view, occurring at frequencies up to the m th harmonic of the nutation frequency. These are not discriminated against by the reticle, since the reticle passes the average intensity over its area, and this average intensity varies as the field of view is nutated around. The averaging process introduces some smoothing of the higher order intensity gradients in the background, but the discrimination is not nearly as marked as when the reticle is rotated and the background remains fixed. This means that a greater burden is placed on the electrical filter when a stationary reticle is used.

Section V. IR SEEKER ENGINEERING

Members of this project have made visits to various service laboratories and contractors concerned with this problem. A list of visits of concern to the air-to-air program is given here:

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Topic Discussed

NAMTC	9-12/14-51	DAN-3	G.B.B.M.S	
NOTS, NAMTC, Hughes	9-17-51			
North American	to	Overall Program	Full Committee	
Northrop, Rand	9-21-51			
NOTS	11-10	Sidewinder	LS.	W.P.
			R.H.	W.A.
Hughes	11-14	Falcon-IR Guid.	L.S.	W.P.
			R.H.	W.A.
Aerojet	11-15	DAN-3	R.H.	W.A.
North American	11-15	Star tracker work	R.H.	W.A.
		and Navaho		
Servo Corp.	11-16	A-4, A-5	Majority of Committee	
NOTS	1-7-52	Sidewinder and	R.H.	W.A.
		Atms. Trans.		
Hughes	2-18	IR seeker	R.H.	W.P.
				W.A.
NOTS	2-19	Sidewinder A and	R.H.	W.P.
		B heads		W.A.
		OMAR		
Aerojet	3-10	DAN-3 and Sparrow	R.H.	W.A.
HYCON	3-12	DAR-1		W.A.
APL	3-21	Terrier	D.F.H.	L.S.
NAMTC	4-17	IR work and facilities	W.P.,	L.S.
Raytheon and CEREL		DAN-3 and Sparrow		W.A.
Aerojet	6-6	DAN-3		W.A.
Aerojet	6-11	DAN-3	W.P.	W.A.
Great Britain	6-4 to 6-18	BLUE JAY and others	C.T., L.S., D.F.H., G.B.B.M.S.	
NOTS	6-19	Test Program-	R.H., W.P., W.A.	
		Sidewinder		
Baird Assoc.	6-26-52	Air tracking	J.H.V.V., L.G., R.C.	
Photoswitch	8-27-52	Mosaic seeker	D.F.H.	
Aerojet	9-17-52	IR seekers	L.S.	
NOTS	9-18-52	Scanners	L.S.	W.P.
			R.H.	W.A.
HYCON	9-19-52	DAR-1	L.S.	
			R.H.	W.A.
Douglas	9-19-52	Jet shielding	R.H.	W.A.
		Afterburners		
BuAer	10-1-52	DAN-3, DAR-1	W.P.	R.H.

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All seekers suitable for the air-to-air mission now in existence have certain features in common. These are:

- (1) The use of an uncooled PbS cell as sensitive element.
- (2) Approximately 3" diameter optics.

There is, therefore, no fundamental reason for any difference in range between these systems. For quantitative data on ranges, see Section II.

As is pointed out elsewhere, PbS cells are sensitive only to about 20% of the total thermal radiation of potential air targets. Thermal bolometer detectors, while sufficiently fast for this application, have a higher noise equivalent power input so that the range is limited to ~1 mile against air targets.

PbSe or PbTe cells potentially offer the possibility of using all the available energy. The use of devices sensitive at wavelengths $> 2.7\mu$ is of particular utility in connection with the air-to-air problem since it permits almost complete elimination of the cloud background by filtration. It is recommended that fundamental work on detectors, particularly PbSe, be expedited for this purpose.

The various development groups differ considerably in their emphasis on the type of target signal (active heat source, silhouette, sun reflection) which the particular design aims for. This leads to differences in design, notably in choice of filtration. These design choices affect in general only components which can be changed easily.

It is our feeling that it is premature to make definite decisions as to the best source of signal.

As long as no detector of sufficient sensitivity in the range $\lambda > 2.9\mu$ exists, effective radiation reduction from jet airplanes by shielding may constitute an effective countermeasure. Hence the daytime silhouette and reflection signals constitute an effective reserve. Further improvements in PbSe or other long wavelength detectors would make heat screening practically impossible.

In the Sidewinder, and also in the Falcon (IR guided) missile, where the overall guidance system has been considered, a system of proportional navigation is used. The scanning telescope generates an error signal proportional to the "error angle," i.e., the angle between the sight line and telescope axis. This signal is applied to a torque generator which precesses the (gyro mounted) telescope toward the line of sight. Simultaneously, in the Sidewinder, a torque is applied to the steering surfaces that is proportional to the same signal, and in the Falcon the steering surfaces are positioned in proportion to this signal. It

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can be shown that either system in linear approximation will lead to a system of proportional navigation, i.e., the rate of change of the flight path angle is proportional to the rate of change of the line of sight angle. Such a course is characterized by the fact that it tends to a "constant bearing course," i.e., a rectilinear course with proper lead for a non-maneuvering target. The required missile acceleration decreases as such a collision course is approached. The rate of approaching a collision course is defined by the "navigation constant"; this must lie above a certain value in order to correct the initial launch error value and any further errors (for example, due to target maneuvers) rapidly enough, and it must be below a certain limit to avoid instability.

The guidance system described above contains no reference whatever to the missile frame. This is essential in order to keep yawing and pitching of the missile from introducing noise in the tracking loop.

For the IR systems considered, the maximum permissible error angle may be less than the missile yaw immediately after launching; this would require that the seeker be uncaged and tracking prior to launching, and it would thus be necessary that the seeker withstand launching accelerations (up to 80 g in some cases).

In order to avoid cross talk between the two steering signals, it is necessary that the roll-rate be reduced to a rate well below the speed of the control loop. In practice this requires a system of roll-damping (not necessarily roll stabilization). A seeker head alone thus cannot constitute the complete guidance control center.

The seeker is protected from the airstream by an IR-dome. This is a simple glass hemisphere in the case of Sidewinder with consequent increase in drag. Hughes proposes the use of a hemisphere of smaller diameter than the missile with an ogival transition from body to hemisphere. Attempts in this country to use flat-sided pyramidal domes have been unsuccessful due to "ghost images." The use of points and spider ogives ahead of hemispherical domes has been suggested.

Although further work on the IR-dome problem is indicated, the solutions involving the hemispherical dome are not a serious detriment to overall performance at present.

There exists at this time factual disagreement as to the nose temperature in flight. If the highest quoted values (600°F.) are correct, this might cause serious noise. If the lower figures (300°F., measured at NOTS) are correct, the situation is satisfactory.

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None of the present guidance systems employs means of acquisition by wide angle search. This has the following consequences:

- (a) The seeker must be locked on to the target before launching and has to withstand launching accelerations.
- (b) The useful range of the missile is defined by the reliable lock-on range of the seeker.
- (c) If the target is lost during course, due to a temporary interruption of the signal, the mission is lost.
- (d) Initial sighting of the target must be accomplished by other means. Under combat conditions, and especially at night, this may be difficult.

It is not at all certain that adding acquisition by wide angle search will be successful, at least in daytime. It is quite possible that the number of false targets (including the sun) is so large that search is impractical. It is recommended that this be studied carefully before technical plans for adding acquisition to seeker systems are laid down.

For the time being, we must accept the above limitations.

In the following no attempt has been made to survey all air-to-air seekers.

1. The Sidewinder Missile (NOTS - Inyokern)

A. Description

- a. The Sidewinder missile is a guided missile adapting an IR seeker head to an existing (HPAG) 5" rocket. Large quantities of the rocket are available which can be backfitted. The round can be launched from any aircraft capable of carrying the standard Navy rockets.
- b. The Sidewinder is characterized by simplicity of mechanical and electronic design. Special features in this respect are:
 - (1) A propellant grain is used as power source for a generator and to activate the control surfaces;
 - (2) only 3-5 vacuum tubes are used in conjunction with magnetic amplifiers;
 - (3) roll damping is achieved by the installation of "Rollerons" directly in the fins. The result is that only one gyro is used.
 - (4) Pneumatic controls are used.

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- c. Sidewinder incorporates a scanning disk which discriminates well against sky gradients but not against sharp cloud edges at the present time. Either positive or negative contrast target signals can be used. No color filtering is used at present.
- d. The airframe of Sidewinder and the IR dome do not represent an optimum design.
- e. The warhead can be as much as 45 lbs. but present plans call for a 10-lb. head (See Part III) in the interest of a higher rate of turn.
- f. Reflective optics (Cassegrain) are used; the field lens is of glass.
- g. The Sidewinder is 112" long, 5" d. with 21" wing span and weighs about 150 lbs.

B. Status (Sept., 1952)

- a. Sidewinder has undergone two completely guided air-to-air flight tests to date. Launching and lock-on characteristics were satisfactory, but the tracking was interrupted due to power supply failure in both flights and gyro unbalance in one case.
- b. Sidewinder has been fired with successful program guidance.
- c. Sidewinder has been fired successfully with photocell guidance against the sun.
- d. Extensive tracking tests have been done with a Sidewinder controlling a SCR584 radar with tracking accuracy of about 1 mil.
- e. Sidewinders have been fired against nylon restraining ropes while tracking successfully on a heat source.
- f. Two types of seeker heads have been used; the second, built by Avion Mfg. Co., will probably be used in the first production models. The first two units tested against drones utilized hand-made heads of an earlier type.
- g. Ten complete experimental production models will be built by Philco by October, 1952. Twenty additional units will be built thereafter.
- h. Fuzing plans are indefinite; the first experimental models will have contact fuzing. An active optical VT fuze is being considered.

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2. DAN-3 (XN-1) (Aerojet - BuAer)

A. Description

- a. The DAN-3 (XN-1) is a seeker head for experimental study. It provided early and important evidence that IR tracking of aircraft can be accomplished at ranges of tactical interest. From its properties it is clear that considerable redesign is necessary before it can be incorporated in a missile guidance system.
- b. The DAN-3 (XN-1) employs a simple conical scan without any background discrimination.
- c. The DAN-3 (XN-1) generates two signals; one is proportioned to the difference angle between the seeker gyro axis and a free reference gyro; the other is the electronically generated derivative of the first. For a proportional navigation system only the sight line rate is needed, and this can be obtained directly from the seeker gyro torque. The reference gyro is unnecessary.
- d. The DAN-3 (XN-1) cannot withstand launching acceleration.
- e. Transmission (glass) optics are used.
- f. DAN-3 (XN-1) operates on positive or on negative sources (but not both) depending on how it is set.

B. Status (Sept., 1952)

- a. The DAN-3 (XN-1) has undergone satisfactory tracking tests with about + 1 mil accuracy at ranges up to 5 miles at night.
- b. The DAN-3 (XN-1) has achieved excellent detection range particularly at night (8 miles).
- c. Seventeen production models of the DAN-3 (XN-2) (essentially DAN-3 (XN-1) with small modifications) are being built.

3. IR Guidance for Sparrow

A. Description

- a. The "Sparrow" family of missiles is designed at present in three modifications (Sparrow I, II, III) employing different types of radar guidance systems.

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- b. The present plan is to adapt IR guidance to the control system of Sparrow III. Since Sparrow III already has a space stabilized platform, only the cell, IR optics, and IR dome need be substituted for the radar antenna.

B. Status (October, 1952)

- a. Engineering plans for the purpose of adapting IR optics to the Sparrow III (Raytheon) are under discussion.

4. The A-4 Seeker (Servo Corp. - USAF)

A. Description

- a. The A-4 seeker is nearly identical to the DAN-3. It employs a simple conical scan; the scan amplitude can be changed from 5° to $1\frac{1}{2}^{\circ}$ as soon as a signal is acquired.
- b. No background discrimination is used.

B. Status (Sept., 1952)

- a. A unit has been delivered to Wright Field for approval.
- b. No systems engineering is known to us.

5. The "BLUE JAY" (De Havilland Propellers, Ltd.)

A. Description (All information tentative)

- a. The "Blue Jay" is a short-range air-to-air guided missile designed as a complete system specifically designated for IR guidance.
- b. Blue Jay is to employ cassegrain reflective optics and a scanning system similar to Sidewinder.
- c. The scanner may be used with sectors differing only in absorption, in order to use color filtering to as great an extent as possible. 2° view angle is planned, with 35° half seeker angle. It is planned to use only the positive target signal and to discard the silhouette signal. This will eliminate the problem of cloud background but restrict its use to the tail cone of the target.

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- d. Blue Jay is to be 8-3/4" maximum diameter, 10' long, with 40-lb. warhead, and weight 245 lbs.

B. Status (Sept., 1952)

- a. Blue Jay is only in the planning stage, but the entire system is being developed simultaneously.
- b. A prototype seeker exists.
- c. First flight tests are planned in 18-24 months.

6. "Falcon" with IR Guidance (Hughes - USAF)

A. Description

- a. A seeker has been constructed using a scanning system derived from the Hughes Star tracker system. This seeker uses a symmetrical chopper to provide modulation of a target signal and background discrimination; a "nutation" motion, much slower than the main chopper, provides scanning.
- b. The seeker head is gyro mounted and employs reflective optics.
- c. The plans for adapting the seeker to the "Falcon" missile are not definite at this time.
- d. Falcon is a high performance air-to-air missile, 6 1/2" diameter with 6-lb. warhead and contact fuzing.
- e. The seeker will probably be used with filters.

B. Status (Sept., 1952)

- a. The Falcon seeker is in an experimental design stage.
- b. The seeker head has already undergone successful tracking tests controlling a SCR584 radar.

7. Other Seeker Programs

Several other seeker programs have been studied which are designed for missile applications. Those that employ PbS photoconductors as mosaics or in

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multiple units possess a fundamental difficulty in that the individual units or elements of the mosaic are, at the present stage of the cell art, quite nonuniform in sensitivity. Thus even a perfectly uniform image leads to a signal, and by the same token additional noise arising from the nonuniform sensitivity is always present when the system is used as a scanner.

Two devices that fall into this category are the Photoswitch Mark IV seeker (see the Air Force Technical Report No. 5854), and one of the Baird Associates seekers. Both of these may be expected to suffer from the additional noise mentioned above, unless extremely uniform cell characteristics can be developed. The noise figure of the Photoswitch mosaic is at present quite high. For this reason the range of a seeker using this tube is not sufficient for practical use at present. Although the mosaic tube and associated programs are valuable contributions, it appears to be undesirable to engage in actual seeker development until the physical constants of the tube are satisfactory. This is a case where the basic emphasis should not be on the development of a seeker but on the development of an efficient scanning process for the purpose.

An additional device recently contracted for (Hycon Manufacturing Co.-BuAer) is the AN/DAR-1. This device attempts to avoid the conventional gyro-mounted narrow-field seeker with a wide field-of-view unit mounted rigidly in a missile. Target position information is generated by dividing the field into lobes by optical means.

A device of this kind suffers from certain limitations:

- a. It will have a small range since only a small fraction of the incident energy can be gathered into the cell. This limitation is fundamental and arises because the seeker has a very wide field of view. (The specified sensitivity for the AN/DAR-1 corresponds to a range less than 100 yds., which is shorter than it need be.)
- b. It defines the sightline relative to the missile airframe. This is basically undesirable because of the spurious signals introduced by missile pitch and yaw.

The AN/DAR-1 appears to be a case where work was undertaken before either the fundamental problems or the possible applications had been thought through adequately.

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Section VI CONCLUSIONS AND RECOMMENDATIONS

1. We believe that the use of IR for the guidance of air-to-air missiles is technically feasible.

2. We believe that the application of IR guidance to the air-to-air missile problem offers very great promise with respect to cost and maintenance of large numbers of effective missiles.

3. It has been amply demonstrated (DAN-3 (XN-1), Sidewinder, Falcon IR seeker) that tracking of aerial targets is possible at ranges of interest to the air-to-air mission. It is thus unnecessary to develop new seekers for this or similar purposes unless they incorporate new ideas or unless they constitute a part of a complete weapon system.

4. Seekers for missile use based on other principles should be developed only if they do not have limitations precluding their application for missile use. Such limitations exist in the Photoswitch Mark IV seeker.

5. Cancel the AN/DAR-1 seeker as being fundamentally unsound.

6. DAN-3 (XN-1 or XN-2) is a satisfactory target tracker. It is not suitable for missile use without re-engineering.

7. Studies aiming at the incorporation of IR optics into the guidance system of Sparrow III should be continued. It is recommended that the best available technical assistance be provided for this program.

8. The "Sidewinder" program is well conceived and shows excellent promise. It should be continued at the maximum effort.

9. Competent work on the IR-dome problem for supersonic missiles should be encouraged.

10. The development of IR homing for "Falcon" should be supported with the recommendation that the economies made possible by the use of IR be fully exploited.

11. The shielding of IR sources on military aircraft, including those arising from the use of a jet afterburner, should be improved as far as possible, as a countermeasure against enemy use of IR-guided missiles.

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12. It is recommended that information on vulnerability of aircraft to IR air-to-air missiles be widely disseminated to the aircraft and engine industry, in order to encourage the incorporation of IR source reduction at an early stage in design.

We believe that the following basic program, of importance to the air-to-air problem, should receive support:

- a. Development of detectors which are sensitive at wavelengths greater than 3 microns, and which can be made in quantity.
- b. Fundamental scanner studies, particularly directed toward the discrimination against background based on the different shapes and intensities, or spectral distribution, of target and background.
- c. Background studies, which should be extended to include the earth, sea and tops of clouds.
- d. The study of possible modulation of jet radiation at acoustic frequencies.

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INFRARED WAKE DETECTORS FOR SUBMERGED SUBMARINES

D. M. Dennison

It has been known for a number of years that it is possible to detect the wakes of submerged submarines through the use of infrared radiation. It is found that the wakes are either slightly warmer or slightly colder than the surrounding surface water and consequently when viewed in the infrared they stand out as being either bright or dark lanes across the ocean. The mechanism of the production of a wake appears to be simply the one of bringing up some of the deeper water to the surface, mainly due to the action of the propellers. If there exists a temperature gradient with depth, as there usually is, the wake will obviously be warmer or colder than its surroundings.

The wakes are several hundred feet broad, their average temperature differs from the neighboring surface water by only a small amount and there exist local temperature fluctuations both within and without the wake which are usually many times larger. For these reasons it seems impractical, although perhaps not impossible, to construct a wake detector which operates by measuring directly the temperature of the water. An infrared seeker, on the other hand, can be carried in an aircraft and can survey the surface from a height of several thousand feet. At this height the wake appears relatively narrow and most of the local fluctuations of the surface temperatures will be automatically averaged out.

Up to the present, the British have concentrated their efforts on the determination of temperature gradients and on the direct measurement of the wake temperatures. This work has been useful and promising and they are now constructing an infrared detector using 24" mirrors which they wish to fly at 300 knots at 2,000 ft. altitude. The pioneer work in this country has been done by Mr. H. L. Clark and Dr. J. A. Sanderson of the Naval Research Laboratory. The progress which they have achieved is substantial despite the fact that their work has also revealed the great inherent difficulties of the problem. Since the bulk of what is known about submarine wakes depends upon their experiments, it may be helpful to describe these in some detail.

The apparatus with which many of the recent measurements were made contained an optical system consisting of two 24-inch parabolic mirrors. Arrays of thermocouples forming two thermopiles having areas of 1 x 1 inches were mounted in the focal planes of the mirrors and fitted with windows of rock salt and silver chloride. The response of the thermopiles and windows was

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essentially uniform from 1.5μ to 16μ but a filter was used which effectively cut off all radiation with wavelengths shorter than 4μ . The mirrors were rotated in such a manner that, from a height of 2,000 feet, each thermopile looked down and traced out a circular path on the surface of the sea with a radius of 1,400 feet. Both thermopiles traced the same path, but one preceded the other by about 750 feet. The signals from the thermopiles were partially differentiated, amplified and presented to three different types of recorders. The method of displaying the results, while quite sufficient for research purposes, tended to be confusing and would not be suitable for an operational device. The whole apparatus together with its wind screen was quite bulky and for this reason as well as because of the desirability of a low air velocity it was mounted in a blimp (M-2).

An initial series of tests was performed on the wakes produced 150 miles off Atlantic City by the submarine USS Irex in May, 1950. During the tests a quarter moon was out and the weather was hazy to 5,000 feet. The sea was calm (State 1). As a result of these tests, the following facts were established.

1. It was possible to detect and map the wake of a submarine under the conditions:

- a. surfaced and underway at 6 knots
- b. schnorkelling (submerged 60 ft.) at 6 and at 4 knots
- c. periscope up but not schnorkelling (60 ft.) at 2 and at 4 knots
- d. submerged (150 ft.) at 6 knots.

2. The signal produced by the wake was from 4 to 5 times the noise--this latter being almost equally divided between instrumental and random noise from the surface of the sea.

3. The temperatures of the wakes appeared to differ from that of the surrounding sea surface by amounts of the order of a few hundredths of a degree centigrade, and in these tests were generally colder. Since oil slicks also produced signals, it was felt that at least in some cases the signal from a wake might be due to a different emissivity rather than to actual temperature differences.

4. The wakes grew rapidly during the first 10 or 20 minutes to a width of about 800 ft. and then appeared to remain constant. They were measured up to lengths of 12,000 yds. and ages of more than an hour. For one reason

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or another (usually the presence of surface vessels) none of the wakes in these tests was traced out to the point at which it disappeared.

A second series of tests was conducted in April, 1951, over the Gulf Stream in the Key West area. The signals from the wakes were generally smaller (usually by a factor of the order of 2), but in spite of this, wakes of submerged submarines were measured up to lengths of 20,000 yds. and ages of 2-1/2 hours. In some cases the wakes were warmer and in others colder than the surrounding sea. During one test a light rain was falling, but this seemed only to enhance the signal, due probably to a lowering of the surface temperature of the sea. Although the wakes were undoubtedly observed, the operation of the device was nevertheless marginal and could in its present form only give results in the hands of trained laboratory personnel.

The present form of the wake detector is subject to the following limitations, some of which may be inherent in all infrared wake detectors:

1. It can only be operated at night since in the daytime the sea noise--principally due to sun glint--is several orders of magnitude greater than it is at night and completely obscures signals from wakes. Mr. Clark has suggested that since the spatial distribution of the infrared and of the visible sun glint is the same, and since the radiation from the wake is almost wholly in the infrared, it may be possible to employ a discriminator which will then allow daytime operation. At present this is only a suggestion and may or may not prove feasible.
2. Wakes are also left by surface ships and although they are generally broader than submarine wakes they may be very confusing.
3. Long thermal streaks which simulate wakes are often found in the open sea and are of natural origin. These may severely limit or even eliminate the usefulness of the infrared detector as a method of hunting submarines, unless a method of distinguishing them from true wakes can be developed.
4. The present signal to noise ratio is small and it takes a man with considerable experience to interpret the recordings of the detector. The signal from wakes seldom appears to be larger than the random sea noise by a factor of more than 10, and frequently is much smaller. For this reason the infrared wake detector may always be marginal or nearly so in its operation.
5. The measurements of wakes were made under relatively calm conditions (sea State 1 or 2) and it appears probable that the wakes would not survive long in a moderate sea. The British, from their measurements of water temperatures, concluded that it would not be possible to observe wakes following a storm.

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6. The present apparatus is bulky and is designed for low air speeds. Many changes will have to be made in the construction of the wake detector before it can be installed and flown in a fast aircraft.

At the present time three wake detector programs are known to us.

The British, who place the wake detector second highest on their infrared priority list, are engaged in measuring near-surface temperature gradients in a variety of waters. Most of the work will be on sea background with occasional submarine trials. In addition, as mentioned before, the British are constructing an aircraft unit utilizing a 24" mirror. This differs from American equipment in that it is planned initially to use a cooled lead telluride detector and eventually the superconducting bolometer which is under development at TRE.

The Servo Corporation, sponsored by BuAer, is constructing two models of a wake detector, the AN/AAR3, designed for blimp mounting which will be available for the collection of basic data.

The N.R.L. group is constructing a wake detector whose optics consist of a 100-inch mirror in conjunction with a thermopile 4 x 4 inches in area. It is believed that with this instrument the noise will be solely that due to the sea background and that consequently accurate measurements can be made both upon real wakes and upon the thermal streaks which simulate wakes. As already mentioned, the instrumental noise in the earlier apparatus was as large as the sea noise and consequently it was not possible to measure the latter accurately. On the basis of the results they hope to obtain, it presumably will be possible to specify the factors which would have to be incorporated into any successful wake detector and to forecast its performance. This information will enable a far more accurate assessment of the military importance of the infrared wake detector than is possible at present. It is recommended that the N.R.L. measurements be supplemented by a program of determining sea gradients similar to that which the British are pursuing but under conditions and in waters of particular interest to ourselves.

On the basis of the evidence now at hand, the Metcalf Committee recommends a research program on infrared wake detectors be given high priority but that, at the present time, the production of a wake detector for service use be given low priority.

In arriving at this conclusion, the Committee gave particular weight to the following considerations:

a. The military importance of the problem of the detection of submerged submarines is so obvious that it needs little comment. Every program,

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infrared or otherwise, which might lead to its solution should be actively and vigorously pursued. This conclusion is of course subject to the conditions that the program be sound technically and possible operationally.

b. The present infrared wake detector is marginal in its performance, and shows many serious limitations. It is possible that certain of these limitations can, in their very nature, never be overcome. Nevertheless, it has been demonstrated that an infrared wake detector can detect and display submarine wakes over distances which are of real military significance. The present rate of actual sweep--of the order of 40 square miles per hour--is small, but when the length of the wake is taken into account, the effective rate is perhaps ten times as large. In principle there seems to be no reason for believing that this rate might not be considerably increased in future models, e.g., to something of the order of 2,000 square miles per hour.

c. The N.R.L. group who developed the present detector and who are now assembling the 100-inch model have shown technical skill, ingenuity, and enthusiasm for their work. They have constructed several models, each one designed on the basis of the performance of the preceding one. They should be actively encouraged to continue the project along the lines which they have established.

In evaluating the importance of this development, account was taken of the fact that (a) conventional sonar search (3,000 yd. range, 15-knot ship) yields a search rate of approximately 50 sq. miles/hour, (b) passive listening systems are satisfactory for schnorkelling but are less suitable for submerged submarines, (c) passive listening arrays usually include a fixed installation or are submarine mounted. Conventional arrays have a range of eight to ten thousand yards. (d) Newer arrays may have ranges of 100 miles if optimistic estimates are accepted. In this case bearing only information might be available from a sea area of approximately 11,000 square miles. The same area could be surveyed and submarine positions noted in approximately 5 hours if it is assumed that the eventual wake detector is flown at 300 knots at 5,000 ft. altitude, sweeps a 2-mile wide sea path and that submarine wakes have an average component of length of 2 miles perpendicular to the sweep path. Of course somewhat greater efficiency could be obtained if the approximate course of the enemy submarines were known.

Under favorable conditions (i.e., smooth sea) airborne radar can detect a schnorkelling submarine up to a range of about 15 miles and hence can achieve the high sweep rate of 9,000 square miles per hour. The disadvantage of radar, however, is that it is unable to detect a completely submerged submarine and it is relatively easy for a submarine to detect the approach of a radar bearing air-

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craft before it comes within range. These remarks illustrate the caution with which sweep range in itself should be taken as the sole criterion for the hunting of submarines. The point is that, as far as we know, there exists at present no device for the detection of submerged submarines which is satisfactory in all of the following ways: (a) detection of submarines with certainty under all conditions, (b) does not give false indications, (c) has a high sweep rate.

Conclusions

Despite the great technical difficulty of constructing an infrared wake detector for service use and the possibility that it will always have a marginal performance, the problem of submarine detection is urgent and we believe that no other device has been proposed which can really be considered satisfactory and adequate for the detection of submerged submarines at reasonable rates of search. In addition, if the enemy carries radar intercept equipment, it is the only device which promises high search rates without warning the submarine before it comes into search range. For these reasons we strongly recommend the continuation of a research program on infrared wake detectors. Construction of prototype detectors for service use is, however, not warranted as yet.

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AIR-TO-SURFACE APPLICATIONS OF INFRARED RADIATION

R. H. Cole, D. R. Corson, B. McDaniel

1. Introduction

In this section, applications of surface infrared radiation detectable from the air are evaluated. It is possible to state with assurance that such applications are entirely feasible under some circumstances but it is necessary to recognize the fundamental liability that fog or cloud cover will make surface radiation undetectable and devices depending on it inoperative, and that there are other significant limitations.

2. Target-background Radiation Characteristics.

Although measurements of radiation are not an air-to-surface application per se, a discussion of available information necessarily precedes consideration of thermal mapping and passive infrared guidance. This is because the strengths of target and background signals inherently set limits on such mapping or guidance and their usefulness will be significantly restricted by these limits in many circumstances.

a. Radiation from the Water.

The radiated energy density in the wavelength region 8-15 microns at an altitude of 10,000 feet is of the order 5×10^{-7} watts/cm.² for an aircraft carrier and 1×10^{-7} watts/cm.² for a destroyer or destroyer escort. These magnitudes are in reasonable agreement with estimates of net radiation from decks 10-20°C. different in temperature from the water background if allowance is made for atmospheric absorption.

These signal strengths are adequate to make passive detection feasible, but it should be emphasized that they will not be realized under all conditions. The decks of ships are hotter than the water surface on a sunny day and cooler at night, so that at some times of the day ship and background temperatures are so nearly the same as to be indistinguishable.

Clouds or overcast will also reduce contrast. Even if the surface can be seen, overcast will reduce solar heating during the day and radiative loss at night, thus decreasing the signal strength in either case. Illumination of low-flying clouds and reflecting water (and land) surfaces will give serious back-

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ground signals under many conditions. For these reasons, IR detection will be generally more reliable at night.

b. Radiation from Land.

The signals from such ground targets as power plants and buildings appear to be in the same general range $1-5 \times 10^{-7}$ watts/cm.² at 10,000 feet. The nature and magnitude of competing background signals must be better known before the feasibility of IR missiles against land targets can be determined. Studies of background radiation are desirable for this problem, and would also give information of great value in considering surface countermeasures against IR guided missiles.

From the foregoing, the important question under most conditions is clearly that of how well targets can in principle be distinguished from background. There can be no single answer because of the diversity of possible targets and variability of weather, time of day, and background. Existing data need to be made more generally available and more data are needed.

3. Thermal Mapping.

The limited amount of work which has been done to explore the field of thermal mapping serves to emphasize its importance for two purposes: reconnaissance and obtaining of basic information about radiation characteristics of surfaces.

It appears that practical infrared thermal reconnaissance units are feasible at the present time, and merit consideration for such applications as battlefield surveillance at night, which we understand to be an important problem.

It has been pointed out in Chapter 2, Volume II that existing devices utilizing thermistor detectors are faster than radar for mapping. If the detector were changed to lead sulfide, another factor of ten in speed would be gained; the loss in sensitivity would chiefly affect objects with temperatures near that of the background and would not decrease markedly the ability to locate militarily important targets such as power plants; the contrast between such targets and the background would, in fact, be increased. Since dry ice or liquid air cooling for the cell does not seem impractical in a reconnaissance unit, a cooled lead telluride detector could be used with a further significant gain in speed and with a sensitivity at least as great as that obtained with the thermistor bolometer. It is recommended that the utility of such units be explored.

In addition to its use for reconnaissance purposes, thermal mapping is needed for background surveys in order to make intelligent decisions about tar-

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get possibilities for air to surface missiles. This is particularly important for land backgrounds. The reasons for these conclusions are evident from the discussion of the preceding section.

4. Passive Infrared Homing Missiles.

Several developments exist or have been contemplated. Of these, only the Dove has reached an advanced status as a complete weapon, but passive seekers, such as Servo Corporation's A-5, are under development for missile guidance to surface targets. Accordingly, the present status and prospects of Dove are considered in some detail, following which some comments are made about seeker developments.

(a) The Dove

The weapons characteristics of the Dove are in part that "Dove shall consist of an AN-M65 A-1, 1,000 lb., general purpose bomb casing with suitable nose and tail attachments to enable it to home on a suitable target (by means of an infrared passive homing system when released from an aircraft by normal bombing techniques)," and "shall be capable of being dropped by conventional toss, dive, and horizontal bombing techniques" (Dove Quarterly Progress Report No. 18, October 15, 1951, to January 15, 1952).

The project was initiated on a crash basis in 1944 at Polaroid Corporation. The feasibility of IR homing was demonstrated by a series of 70 test drops in 1945 under special test conditions in which guided Dove missiles showed substantially better performance than unguided ones dropped at the same time.

Since 1946, the project has been carried on by Eastman Kodak Co.

The basic seeker mechanism developed by Eastman for this weapon employs conical scan and thermistor bolometer wafers as detectors. Pulse information from the system is used to supply course correction by on-off operation of nose deflectors.

These principles of the system were frozen at an early stage, as was the airframe of the bomb, and deficiencies in both gave rise to a succession of problems in the ensuing development. A series of modifications and elaborations has led to a homing missile with complicated electronics and a number of complete weapons have been built for a test drop program which is now in progress.

This test program has so far consisted in drops from a PB4Y2 in level flight at 15,000 feet. The bombs were aimed at a point 300-600 feet off a ground-

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ed liberty ship with a 30 x 50 foot heated plate on the deck as an infrared target for the missile. In five test drops of this kind in the spring of 1952, a hit and a near miss respectively were obtained with two missiles, two received substantial course corrections which began too late to bring the bombs on or near the target, and a fifth did not see the target. The results thus show some promise under the special conditions of the test, but do not establish that the estimated performance characteristics of the missile can be realized in its present form. Both design and testing have been on the basis of level bombing operations only.

It should be recognized that the drops were from lower altitudes than are likely to be the case in operations, and that the target and background were also favorable for proper operation of the seeker. Further tests of the present weapon should provide some simulation, at least, of less favorable conditions. In particular, an aim point further removed from the target might give a better basis for estimating performance on high altitude drops for which bombing errors might exceed the correction capabilities of the weapon.

It is quite possible that such tests would give evidence that the weapon could be successful against surface ships. While it is possible that heat homing bombs could be employed against ground targets, the feasibility of such use of Dove needs to be considered carefully because target and background are likely to be less favorable for proper operation.

The questions about attacks from high altitude and against land targets arise primarily from the marginal signal to noise ratio of the Dove seeker at 10,000 feet, together with the limited scan rate and relatively long correction time. If the necessary corrections for high altitude use exceed present capabilities, signal to noise ratio would have to be improved to permit a longer correction period starting at higher altitudes, or faster scanning and correction processes would have to be devised. Proper homing on land targets may also demand a better noise situation and improved discrimination against background. A critical examination of the scanning system is in either case prerequisite to any evaluation of the possibilities of using Dove against ground targets.

Several sources of noise contribute to the unfavorable signal to noise ratio of the Dove scanning system at high altitudes. The primary one is the so-called "sine wave noise," which is a spurious signal generated by optical fluctuations as the scanning head rotates. This was reduced greatly from its original intolerable value by relocation of limiting apertures, but is still significant in the present version. Both this effect and temperature gradients in the background produce modulation at the fundamental scan frequency, and vibrational or microphonic effects associated with the scanning head may also. Because the present Dove operation is determined by signal amplitude, all these effects compete with the target signal.

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Signal to noise ratios of the order two or three to one have been stated as likely for the scanning head looking at a representative ship target from 10,000 feet, even with a uniform background. It seems probable, in the light of developments elsewhere since the Dove design was frozen, that a scanning system discriminating against noise could be devised for large distances at least (where the target is nearly a point).

Another limitation of the Dove system is that a blind spot in the detecting element array can give rise to spurious correction signals which under some circumstances are of the wrong sign. In situations calling for large corrections this effect could be serious.

The Dove is a complicated weapon containing some 70 vacuum tubes in a variety of amplifier, computer, servo, and power circuits, together with deflector drives, roll control, seeker head uncaging mechanisms and the like, all of which have been ingeniously packaged at nose and tail of a 1,000 lb. bomb case.

One naturally asks whether all the complication is necessary. Much of the effort and elaboration has been the result of grafting a guidance system on a general purpose bomb not well suited to the purpose, with the consequence that a new tail structure had to be developed and awkward expedients adopted to fit the electronic and deflector mechanisms into available spaces. The decision to use rudimentary on-off scanning signals and a "bang-bang" deflector system has necessitated a series of elaborations in design to reduce the serious troubles encountered.

It appears that pressure to produce an engineered weapon has forced premature design crystallization. The limitations of the present Dove missile are serious enough that in our opinion only urgent and immediate operational needs would warrant putting it in production or devoting large scale effort to its further development. We believe that a considerably better IR surface homing missile could be produced in a reasonable time if a fresh approach were made taking full advantage of existing knowledge and continuing developments in the fields of detectors, scanners, and missile aerodynamics. Whether such a development would be really useful must be decided on the basis of military importance and a critical evaluation of target-background discrimination problems.

(b) The A-5 Seeker

This device was designed by Servo Corporation for terminal guidance of the rocket missile MX-771 ("Capo") on reaching a point some 30,000 feet above a potential target up to 500 miles from the firing point. The thermistor

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bolometer detector is suitable for use against targets at relatively low temperatures. The scanning system is so designed that the field seen by the detector is swept through an expanding and contracting spiral about the scanner axis. Signals received by the detector are identified in direction by arrival time and modulation referred to the rotation. The design provides for a preliminary search phase with spiral scale over a 20° field every 0.8 second, and subsequent homing phase activated by 3 successive signals with 2° spiral scan at a rate of 15 per second.

If the homing head were required to select a target from a large area after long range guidance had brought the missile to a point directly above it, the target-background problem could be serious. Situations are easily possible in which the seeker would find no adequately defined target, would become confused by several real or apparent targets, or would make an undesirable choice of targets. Careful analysis of adequate target-background studies would be essential to determine resultant tactical limitations.

(c) Other Missiles

Finally, the possibility exists that air-to-air missiles as described in Chapter 3 could be useful against ground targets. These employ detectors sensitive in the near infrared and could home on small hot objects such as tank exhaust stubs. As for any passive air-to-surface weapon, some knowledge of target and background strengths is necessary for evaluation of the possibilities, and this could quite possibly be determined by field surveys employing a successful seeker head. The further problem of target acquisition has been discussed in connection with the A-5 seeker.

5. Active Infrared Homing Missiles

Omar is an air-to-ground beam riding rocket.

The tactical need for Omar arises from the fact that at present air-to-ground rockets are fired by "pin pointing" a fighter toward a ground target and then "pulling up" after release of the rocket. This procedure is very hazardous to the attacking aircraft, particularly when attacking tanks, and also when operating against the face of a mountain such as in tunnel attacks.

Omar effectively attempts to increase the range at which the rocket can be released. An IR "projector" of about 1,000 watts power illuminates the target with a 4° cone of radiation. The beam is "coded" to give proper guidance signals.

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The rocket is either a HPAG or HVAR and fitted with "bang-bang" control. An array of four PbS cells pick up the coded signal. Maximum launching altitude is 15,000 feet. Roll rate damping is achieved by "rollerons" as in Sidewinder.

At present the rate of progress of the project is slow. This is mainly due to the fact that a difficulty has been found in the beam coding system so that a new scheme has to be developed. The project is in competition for personnel with "Sidewinder" at NOTS so that at present not too much manpower is available.

6. Conclusions

(a) Infrared thermal mapping units are feasible at the present time which would have the same limitations as photographic units but would be operable at night and faster than radar mapping. The utility of such devices should be explored with the main effort on units employing photoconductive detectors.

(b) Available information indicates that IR surface homing missiles are technically feasible under favorable conditions. Further study of target and background radiation is needed to determine how generally useful such missiles can be.

(c) The weapon Dove does not in our opinion make most effective use of IR techniques. We feel that its further development and production along present lines is justified only if a sufficiently urgent operational requirement exists.

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ACTIVE IR AND IR COMMUNICATION

W. N. Arnquist

The field of active IR in the U.S. essentially began with World War II. A research and development program was conducted under NDRC which resulted in a number of important practical devices, the most noteworthy, perhaps, being the sniperscope. Other developments included IR search light sources, auto-collimators for roadside markers, IR binoculars, and communication devices.⁽¹⁾ These devices saw some military uses during the war which served to emphasize the relative importance of this field. It is interesting to note that the IR viewing devices represent the outgrowth of IR telescope research which was begun in the early thirties and resulted in an operable instrument in 1935.⁽¹⁾

In the intervening years since 1945, active IR research and development programs have been continued in this country, especially by the ERDL, the Signal Corp., and the Bureau of Ships. This has resulted in a number of improvements especially in the development of better image converter tubes and periscopes for tanks. For example, complete tank driving IR equipment, designated by the code name "Leaflet," has been released for production in quantities sufficient to equip all tanks⁽⁵⁾ after present service evaluations are completed. Because of the relatively advanced state of development in this field at the present time, Project Metcalf has not considered it necessary or advisable to make a systematic study of active IR and IR communication. However, in the course of this project, some impressions have been gathered so that this section is included for the sake of completeness. It is to be emphasized that no attempt has been made to cover the subject completely or even to provide a reasonably complete list of the active projects in this field.

Active IR requires a source of IR illumination and an appropriate viewing device. It is useful for "seeing in the dark" without the use of visible radiation, or for transmitting intelligence over limited line of sight distances with more security than visible light affords. The region of the spectrum covered is from just beyond the visible, say 0.8μ , to the beginning of appreciable radiation from ambient temperature objects on the earth. This latter boundary may be taken somewhere in the 3 to 5μ region. In practice, the long wavelength limit of active IR has been only slightly over 1μ as determined by the limitations of the viewing devices. Although there are prospects for extending this limit to perhaps 3μ (or even farther as will be noted) active IR is inherently limited to the near infrared region of the spectrum.

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IR searchlights have consisted of very hot sources, such as tungsten filaments, with an appropriate filter to remove the visible light. The ordinary problems of optics come into the design of these devices. For example, it is usually required to confine the radiation in a relatively narrow beam. This limits the size of the filament which may be employed and the size of usable electric discharge sources, since the latter are difficult to restrict to a very limited region. Consequently, high temperature filaments are used almost exclusively even though much of the radiation is generated in the visible.

The developments in active IR have been limited in practice by the development of IR viewing devices. These have consisted of two kinds; the activated phosphor type of indicator now largely obsolete, and the electronic image converter tubes. In the former, an IR image is formed on an activated phosphor (such as ZnS plus a small amount of Pb - usable out to around 1.3μ) film where it is converted locally to a rather crude visual image without the use of an electronic system. The difference in energy between the IR quanta and the visible quanta is supplied by activating the phosphor with ultraviolet radiation or radium emanation. These devices are inherently less sensitive than the electronic tubes. However, the extreme simplicity of the phosphor type devices is very attractive, so that they have been used where the IR illumination level is relatively high, such as in detecting IR beacons and searchlights, and where simplicity and low weight are very important, as in paratroop operations.

In the electronic image converter tube an IR image is formed on a surface coated with a material which emits photoelectrons. These electrons are accelerated to a fluorescent screen where a visible image is formed. In practice, an electrostatic lens system is employed to produce a reasonably clear image on the fluorescent screen. These devices are naturally limited by the long wavelength cut-off of the photoelectric material. No practical materials of this sort have been discovered which are appreciably better than the cesium-oxygen-silver surfaces developed during the war with a cut-off at about 1.2 microns. In these tubes the designer can increase, to some extent, the brightness of the visual image by increasing the accelerating voltage. However, this usually poses new problems in the power source, which is preferably portable, and in the tube design. Also, the electrostatic lens can be chosen to reduce the size of the image somewhat and increase the brightness. Some of the characteristics of the current tubes of this type are given in the following table⁽³⁾ where it will be noted that magnifications less than unity are used and voltages up to 20,000 volts.

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PHOTOEMISSIVE IMAGE TUBES

Used in near infrared equipment for detecting radiation having wavelengths from 0.8 to 1.2 microns.

- 6032 - Maximum Voltage = 20,000
 Number of Electrodes = 3
 Magnification = 0.515
 Center Resolution Lines per inch = 460
- IC-16-3 - Maximum Voltage = 16,000
 Number of Electrodes = 3
 Magnification = 0.75
 Center Resolution Lines per inch = 625
- IC-6-2 - Maximum Voltage = 6,000
 Number of Electrodes = 2
 Magnification = 0.68
 Center Resolution Lines per inch = 460
- IP25G-2 - Maximum Voltage = 16,000
 Number of Electrodes = 7
 Magnification = 0.5
 Center Resolution Lines per inch = 300
- IP25-A - Maximum Voltage = 4,500
 Number of Electrodes = 5
 Magnification = 0.5
 Center Resolution Lines per inch = 200

Another type of image converter tube is one which utilizes the photoconductive effect in certain semiconductors. The Germans attempted to develop such a tube during the last war using lead sulfide. Since IR radiation increases the conductivity of this material, rather than liberating photoelectrons, another method must be used to create the visible image. This is done by depositing the PbS film on a network of wires or on a thin conducting sheet, so that the local changes in resistance in the PbS film will affect the potential distribution set up by applying D.C. to the wires or the conducting film. Then, if a homogeneous beam of electrons is allowed to fall on the surface at almost zero velocity, more or less of the beam is reflected in accordance with the modified potential distribution. This reflected beam is then focussed on the fluorescent screen as in the photoelectric type of tube.

In this country progress has been made on photoconducting image tubes notably at Capehart - Farnsworth and RCA. At Photoswitch work is in progress on a far infrared (8-12 μ) image tube using thermistors as the sensitive elements.

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Receivers have been made of the mosaic type where a number of independent sensitive elements are arranged in an array and scanned electronically. Alternatively, a single receiver has been used and optical scanning employed. In these cases the visual image is formed with a separate cathode ray tube.

At RCA Princeton a promising PbS image tube is under development under an ERDL contract. In this the PbS is deposited in a matrix of PbO on an appropriately conducting film backed by a glass surface. The PbO matrix is employed in order to increase considerably the resistance of the photoconductive layer in order that the local charge deposited by the scanning electron beam may not leak off too rapidly. However, this resistance is of the proper value so that this leakage is increased when the conductivity increases in response to IR radiation. Thus the potential of the surface is modified and that part of the electron beam which is reflected responds to the modified potentials and causes a visible image on the fluorescent screen. These tubes are showing such promise at the present time that considerations are being given to the development of similar PbSe and PbTe tubes which would be cooled.

The advantage of the photoconductive type image converter tube is of course that it extends the usable spectral range to about 3μ for PbS. The use of PbSe and PbTe can extend this range considerably farther (Chapter 1, Part II). However, this generally is of more interest in passive IR systems as it begins to include the longer wavelength radiation emitted by bodies that are warm or are near ordinary temperatures.

The applications of active IR and IR communications are numerous. For example, the Leaflet equipment allows tanks to drive at night and engage in limited combat operations. With the IR binoculars jeeps, tanks, etc., may be driven at night up to speeds around 30 miles/hr. With powerful IR searchlights an object may be illuminated from a considerable distance (of the order of miles) as a guide to tanks or troops. The use of IR equipment in amphibious operations is obvious. Also, in air-to-air communication, where electronic silence is required or the type of security provided by IR is of importance, there may be some advantages. For example, the Air Force is making a study of such a communication application in air-to-air refuelling operations. A rather special application is the IR transit which is undergoing service tests at this time. With a reflector, ranges up to 2,000 yds. are obtained and with beacons these can be extended to 10,000 yds.

The following represent examples of current active IR devices which have come to the attention of this Project. They are listed here to indicate the scope of the developments in this field. (4,5,6)

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Sniperscope Set No. 1 - 6062 image tube; range 130 to 150 yd.; wt. telescope and light source 6 lbs. 7 oz., wt. carbine plus sniperscope 14 lbs. 7 oz., wt. battery, power supply and knapsack 19 lbs. 15 oz.; operating time 2-1/2 hours continuous (3-4 hrs. intermittent). Being introduced in Korean theater.

Image Metascope, type XR-3, T-1 (and T-2) - IC-6-2 image tube, one BA-30 battery (2 for T-2); range 4 mi.; wt. 20 lbs. 11 oz. (29 lbs.); operating time 50 hrs. (100 hrs.). Undergoing service tests.

Beacon for Airborne Troops: Mounted on 25 ft. mast, field 360° x 15°; can be coded with one letter; designed for assembly aid in night operations; total wt. 40 lbs.; range with image metascope 4 mi., with Type US/F metascope (phosphor type) 2.5 mi.

IR Transit - IP256 image tube and alidade on tripod; IR source for use with reflector (2,000 yd. range); with beacon 10,000 yd. Undergoing service tests.

IR Spotlight - portable, wt. 15 lbs.; illuminates small area such as a road block; a man 75 yds. from spotlight recognized with Sniperscope at 350 yds.; operating time 4.5 hrs. Being redesigned to improve mechanical construction.

Metascope Type US/F Phosphor surface lead-activated ZnS; Schmidt corrector plate, spherical mirror, radium button for activating.

IR Binoculars - head mounted, wt. 23 oz.; IC6A image tube; power supply batteries 17 oz.; range with 2-250 watt headlights filtered 150 ft.; operating time 10 hrs.; safe driving speed 25-30 m.p.h. Being service tested. Navy considering use by landing parties.

Leaflet II Equipment - IC16 image tubes used.

For Tanks

1. Two binocular periscopes for driver and assistant driver.
2. Two dual beam 100/50 watt headlights.
3. Tank commander binocular periscope (2 power).
4. Tank commander 450 watt, 12", searchlight linker to viewer.
5. Gunner's periscope, 2 power monocular with aiming reticle.
6. Gunner's 1000 watt, 18" searchlight mounted coaxially on gun shield.
7. Three high voltage power packs for viewers.

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For Half Tracks

10 kw. electric generator and 24" carbon-arc, IR searchlight with IR viewer (6032 image tube) for controlling direction of searchlight beam.

For 2-1/2 Ton Trucks

60" searchlight with IR filter and IR viewer (6032 tube).

The Leaflet II equipment recently has been tested by service personnel of the 318th Medium Tank Battalion in a series of exercises at Camp Irwin, California, during the months of May and June. Three platoons of M46 tanks were fitted with this equipment. Various night driving, gunnery and tactical problems were set up. The troops were given field instruction in the use of the equipment before the exercises. While no reports have been issued concerning the results of these tests it is understood that, on the whole, they were very successful. Even discounting somewhat the results because of the generally favorable desert conditions where the dry sand served as an excellent reflector and where the atmosphere usually was quite clear and dry, the officers in charge of the tests were convinced of the suitability of the equipment for operational use. Also some experience in the tactical concepts of IR warfare and the necessary training requirements has been obtained.

IR communication devices are in a relatively advanced state of development. This is indicated by a recent statement from the Panel on Infrared of the Research and Development Board which reads as follows: "The considerable amount of funds and energy that have been spent over the past 8 years in the development of infrared communication equipment has culminated in a system which provides reliability and range exceeding that requested.....". The statement goes on to say that it is doubtful if sufficient service evaluation of the equipment will be authorized. This probably is because the relative need for "electronic" silence is still under discussion in the services at the present time, especially in the Navy. At any rate it is not clear at the present time how much the services need IR communications.

At present the following agencies are undertaking IR communication developments as indicated.

Bureau of Ships - AN/SAC-3 Stabilized Shipboard Installation, broadcast, teletype and code, 0.8 to 2 μ (thallous sulfide) 360° x 6° V field, 4° vertical x 2° horizontal receiver field, range about 13 mi. at night and 5 mi. daytime when visible atmospheric transmission is 60% per mile.

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AN/SAC-4 - transportable voice system for surfaced submarines or landing craft in amphibious operations (directions to boats or swimmers), Cesium cell (.85 to .89 μ) 12⁰ beam for transmitter and receiver, range at 60% visual atmospheric transmission per mile - 5 miles.

AN/PAC-1 - hand held voice transceiver, range 3,000 yd. (5,000 yd. with AN/SAC-4) thallous sulfide receiver, filtered tungsten bulb transmitter.

AN/PAR-1 - hand held aural receiver, range 6,000 with AN/SAC-4 and 4,000 yd. with AN/PAC-1.

AN/PAR-2 - helmet mounted aural receiver for underwater demolition teams - range 1,000 yd. with AN/SAC-4.

Bureau of Aeronautics

A narrow beam transmitter and auto-tracking receiver for voice transmission, air-to-air, is being developed.

Air Force

A study project is underway with emphasis on communications for use during aerial refueling.

Signal Corp.

An experimental pulse communication system is being procured from Northwestern University. Laboratory studies are being made in utilization of circular polarized light for signalling.

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